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I.O. Sinchuk,
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BASED ON WATER DRAINAGE COMPLEXES OF UNDERGROUND MINES

Edited by Sinchuk O.M., D.Sc., Prof.
Multi-authored monograph

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Authors:
I.O. Sinchuk, O.Yu. Mykhailenko, K.V. Budnikov

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Reviewrs: **Rozen Viktor Petrovych**, DSc. (Engineering), Prof., (National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv)

Kutin Vasyl Mykhailovych, DSc. (Engineering), Prof., (Vinnytsia National Technical University, Vinnytsia)

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The monograph considers the issue of increasing the energy efficiency of ore mining processes in mines through the introduction of distributed power generation systems. The pumped-storage potential of underground water drainage is used as a source for generating power. A comparative analysis of various configurations of power systems for mine consumers, including "peak" pumped-storage hydroelectric power plants, with a scheme in which power is supplied only from an external power grid, has been carried out.

The monograph targets electric engineering and mining students, specialists working in the mining industry and research institutes.

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CONTENT

INTRODUCTION

As an industry, power engineering, is a system-forming segment of economy that ensures activity of all other industries and the state as a whole. During the years of Ukraine's independence, the problems of power engineering, both current and previous ones, have never been as urgent for the state as in recent years.

Unfortunately, progress in developing Ukrainian power engineering almost ceased in the 90s of the last century. That period of stagnation of over 30 years has had a very negative impact on both the industry (outdated equipment, old technologies) and power consumers (constant price growth, low quality). The way out of this situation at the country level lies through restructuring centralized sources of power production and distribution, which cannot be implemented, since this requires significant costs (investments) and a quite long payback period.

The so-called distributed power is effective and easy to implement, both from the financial viewpoint and in terms of positive experience of developed countries of the world as besides centralized power supply, it involves sources of small power generation. In some countries, the share of this type of power engineering reaches 50% of total power production.

Transition of industrial enterprises from centralized power supply to distributed generation will allow a significant reduction in power costs by 40-50% according to a number of researches. These steps will enable achieving the expected levels of reduction (stabilization) of production costs of certain products, thus greatly improving the economic situation and competitiveness, both in domestic and foreign markets.

Moreover, given the current situation in Ukraine, which is in the stage of military aggression, when the aggressor targets the country’s energy potential (power plants, power lines), creation of small power facilities will make it possible to ensure functioning of vital infrastructure and people’s basic needs. That is, what yesterday looked like a distant and not quite a priority prospect, today has become a strategically important issue of existence of the state economy and people.

Transition from the exclusively centralized type of power engineering to the distributed and smart one is a strategic vector of change in the energy structure of our state, not in its future, but present vision.

In this context, the state represented by governing bodies and owners of industrial facilities should in the shortest possible time reconsider the philosophy of development prospects of both macro- and micro-energy sector. Special attention should be paid to the use of distributed power generation, creation of micro-grids as an important component of Smart Grid technology.

At the same time, issues of informativeness of ensuring the management process of this technologically difficult complex should be accentuated. This moment will determine the final version of the solution aimed at integration of distributed generation sources into the structures of systems with centralized power supply (integrated power supply systems) and control over their functioning.

Available scientific and technical literature on this issue highlights the main issue of integration of distributed generation networks into the structures of main power supply networks. The choice in favour of this solution is detrmined by the desire to maintain the quality of power when delivering it to consumers.

At the same time, the process of functioning of such synergistic structures looks like simultaneous work to load two sources: centralized and distributed generation.

However, not rejecting the idea of distributed generation, which is used, or rather is essentially planned for implementation in main power grids, but on the contrary expanding the boundaries of this trend, we note that in the tactics of its implementation for the first and second options there are logistical differences.

The quintessence of these differences is that in the second option, development of power supply systems at enterprises aims to minimize the levels of power supply from power systems during peak hours. Thus, expenditures of consumers for power supplied to them centrally decrease. For energy-intensive consumers, this is a significant saving and a real way to reduce production costs of a particular type of products.

SECTION 1. POWER CONSUMERS OF IRON ORE UNDERGROUND MINING ENTERPRISES AS A TECHNOLOGICAL PROCESS

1.1. General data

At the beginning of 2021, over 55% of the total industrial power in Ukraine was consumed by metallurgical enterprises (35%), and their basic raw materials partners – mining enterprises consumed 20% [6]. These figures reflect significant energy intensity of these enterprises. Such an odious fact negatively affects the general state of the economy of mining enterprises, and reduces their competitiveness in the world market of raw materials, where Ukraine occupies a worthy place, which, in turn, allows annually replenishing the state's foreign currency reserves by 60-70% [7].

In the current political and economic situation in Ukraine, this positive trend can vanish, causing tragic consequences for both the state and the people.

One of the most significant factors affecting stability and efficiency of mining enterprises of the raw material base of the metallurgical industry is technical stability of power supply and economic feasibility of energy services received.

The basing component of energy efficiency (energy intensity) of mining in general, and iron ore materials in particular, is mining technology.

According to researches by mining scientists and technologists, available technologies for extracting iron ore materials will not change in the next 50-70 years [8-10]. Meanwhile, functioning technologies of modern mining enterprises with both open pit and underground mining methods imply constant increase of mining depths, which rejects the possibility of a natural decrease in power consumption by these types of enterprises.

Moreover, as proved [11], the process of reducing the levels of underground mining at national iron ore mines in itself determines a constant increase in power consumption. Every year, this increase reaches more than 1 kW/h per 1 tonne of iron ore mined underground [12]. Thus, this odious process actually absorbs those positive trends of energy efficiency segments that can and are achieved at enterprises by introducing a number of trivial energy-oriented local measures.

Of course, the above in no way calls into question the need and expediency of any measures to improve energy efficiency of iron ore extraction. Although the maximum effect of increasing energy efficiency of iron ore production can be achieved only with comprehensive implementation of all possible and affordable measures included in a single centralized automated energy management system of an enterprise [13-19].

According to the functioning technology of these enterprise types, a limited number of energy-intensive consumers are involved in the production process. It is a positive basing point of iron ore mining in terms of developing the scheme and achieving the expected level of energy efficiency, unlike other mining enterprises processing coal, salt, etc. [20-22]. Consumers of these enterprises include compressor stations, skip hoists, a crushing and sorting plant, main ventilation and drainage facilities. These very consumers use more than 90% of the total power, which is consumed by a typical national iron ore underground mine [23].

Such levels are associated with significant material costs of enterprises for the power consumed, which negatively affects the economy of enterprises [10, 24-26].

Considering and evaluating the in-pit conveyor technology of functioning of the above-mentioned consumers, it is logical to potentially classify them as "power consumers-regulators" instead of "consumers".

With this solution, the algorithm of operation of electromechanical complexes (primarily, energy-intensive consumers) is based on a two-unit version of their functioning: a mode with the minimum possible levels of power consumption and the one with the maximum permissible levels of power consumption.

The essence of the approach implies the idea that hours of the day are conditionally divided into periods of "peak" (usually daytime) and "economical" (night time). The solution is that during peak hours, consumers work under the minimal consumption mode, and in "economical" mode – under the maximum load mode. It is this option that is actively implemented at industrial enterprises of Ukraine, including the mining ones.

At the same time, we note that, as a rule, the practice of such solutions is based more on preventive expectation of the effect rather than on justified factors.

Nevertheless, as evidenced by the research results, including those in [27-46], an option of finding ways to solve the problem of energy efficiency at iron ore enterprises, which is analyzed, provides and has already had a certain effect. However, a significant level of potential in this direction continues to exist and should be realized. Moreover, the current scheme of payments between consumers and enterprises generating power with hourly variables within daily tariffs introduced in January 01, 2019, adds considerable creativity to the process of studying this issue.

At the same time, it should be noted that this option of finding ways to improve energy efficiency takes place along with all the other variations in the development of schemes (modes) for functioning of energy-intensive systems and complexes of mining enterprises.

The second modern approach to the problem of improving energy efficiency of mining enterprises is restructuring of existing power grid structures with centralized power supply into thoses with distributed power generation. As noted ahead, this variation is especially relevant under current circumstances.

Mining enterprises possess their own significant basic potential to achieve energy efficiency [47-79]. Among energy-intensive consumers-regulators of iron ore mining enterprises, water drainage facilities that remove water from underground mine workings to the day surface into special tanks are of special importance due to their potential in achieving energy efficiency.

Considering that the above mentioned water drainage facilities consume more than 35% of the total power consumed by an underground mine, it is logical that the problem of energy efficiency of these types of mining enterprises should be solved first of all by these consumers.

However, the stages of such a "simple", at first glance, solution is far from being arbitrary. Based on the conclusions of the research, it can be stated that to obtain a tangible effect on the energy economy of mining enterprises and take appropriate energy-saving measures to change an algorithm of the functioning technology of a water drainage facility, differentiated assessment of the impact of corresponding technological components on water drainage along with a relevant response to control systems is necessary.

The desired level of energy efficiency can be achieved by creating an appropriate automated control system for operating modes of water drainage facilities, which are substantiated and formalized according to factors impacting their functioning algorithm.

At the same time, based on all the same research results, we note that development of the structure and parameters of the algorithm for the functioning of such ACSs has its own system-forming difficulties. The main one is the fact that formation of a unified algorithm for controlling operation modes of water drainage facilities for all underground mines is impossible. It is a natural stochastic process unpredictable both in time and in volumes. For each enterprise, this process of filling underground mine workings with water is characterized by its own system-forming aspects, which, when ignored, cannot allow obtaining a positive solution of developing an effective functioning algorithm of water drainage facilities. However, the idea of developing an individual option of the ACS algorithm should be recognized as irrelevant.

Implementation of smart control in the functioning algorithm of ACS elements to determine and respond to randomness and uncertainty of current changes in technological parameters of the water drainage process seems to be technologically expedient [50-54].

However, even in such a necessary option, the operation of the water drainage complex in the power consumer-regulator mode will not exhaust its positive potential and prospects for these types of power consumers in improving their energy efficiency.

As an active continuation of the process of improving energy efficiency of the water drainage facility, there may occur the following direction: not bypassing, but based on the mode "power consumers-regulators", to supplement this complex in the synergetic version as "power consumer-regulator-producer".

This direction is interpreted as creation of pump-storage power plants (PSPPs) on the basis of water drainage facilities of iron ore underground mines. They should function during peak hours, although this period, if necessary, can be increased. For this purpose, the design of a water drainage facility fully corresponds to that required to develop these types of power plants. At the same time, the relevance of this direction can be supplemented with another modern positive solution. Such pump-storage facilities can become backup sources of power generation not only for the units themselves, but also for the needs of adjacent local territories.

For a number of objective reasons, most of the studies known to the author were conducted based on virtual rather than real-life technological parameters of functioning of water drainage complexes. On the contrary, the "case", analyzed by scientific researches conducted by numerous authors, looks like a purely targeted version designated only for conditions of a particular underground mine. Yet, limited results of these and some other search targets provide a necessary base to conduct further research. This, first of all, implies the possibility of expanding the boundaries of further searches and, secondly, provides an opportunity to obtain unified and integrated results.

The format of this research is built according to the above motivation.

1.2. General issues of power engineering and the impact of the functioning technology of the power market on them

Over the past decades, production of power in Ukraine has been decreasing and at the beginning of 2020 it made 150 000 GW*h against 300 000 GW*h in 1990, i.e., it has halved. Meanwhile, the levels of installed capacities of Ukraine’s power plants have not decreased compared to 1991, but, on the contrary, have increased and are actually equal to about 55 GW [55].

The potential capacities of the Ukrainian electric power industry make it possible to produce about 300 billion kWh of power per year.

The power balance of Ukraine is characterized by:

– decrease of power production volumes in 1990-2000 from 298.5 to 171.4 billion kWh, i.e. almost halved (including TPPs by 2.5 times) with the tendency of potential stabilization;

– reduction of power received from outside Ukraine;

– reduction of power consumption by the industrial sector;

– reduction of power supply outside the state;

– the trend of stabilizing power production volumes;

– stability of production volumes by nuclear power plants;

– growth of generating capacities.

Key requirements for modern general power engineering formed by the world community, include, in particular, its effectiveness declared as "maximizing efficiency of the use of all types of resources and technologies in production, transmission, distribution and consumption of power" [56-62].

Currently, in most countries of the world, the process of steadily reducing the amount of power used to produce a unit of GDP continues. This trend, although in a significant lag behind the EU countries, is also typical for Ukraine. As is known [63], energy intensity of this main economic indicator of the state is largely determined by part of the energy-intensive industry. In the last decade, power consumption by the industrial sector of Ukraine stabilized. Close to this option of stability came energy-intensive types of production, including enterprises of the mining and metallurgical complex.

Such "stability" restrains the pace of reduction of energy intensity of GDP necessary for the state's economy. However, this is not a verdict on the futility of further reducing energy intensity of GDP, but on the contrary, an impetus to intensify the tested and find new ways to solve this global problem for the state. The Law of Ukraine on the Power Market is also aimed at solving these problems [64].

The reform of Ukraine’s power market is associated with acquisition of the status of a Contracting Party in the Treaty establishing the Energy

Community [65]. Fulfillment of the requirements of the Third Energy Package in a timely manner is the main priority for the next period of activity of the United Power System (UPS) of Ukraine within the Energy Community. In particular, with this package, the national regulatory authority is endowed with legal isolation and functional independence from any state, public, private persons, market interests, including persons responsible for management.

It should be noted that when following foreign countries' experience, reforming (liberalization) of the power market and making it competitive leads as a rule to a significant increase in power prices, a decrease in investments in the industry, a subsequent decrease in the capacity reserve and reliability of power supply to consumers.

A number of national scientists in the field of power engineering [57-63] emphasize that at this stage of development of legislation, in particular the antimonopoly one, it is more expedient not to change the "current" model of the power market, but to improve it by introducing mechanisms of centralized impacts on development and functioning of the power system of Ukraine. It is also proved that concentration of market potential primarily in production of power (monopolization of generation) by a certain financial and industrial group contradicts the idea of forming market competition, which underlies the "new" model of functioning and management of the power market.

As evidenced by the results of the first years of reforms, a new already existing model of the wholesale energy market of Ukraine needs to be improved in terms of respecting the economic interests both of suppliers and consumers of power. An important component of this process should envisage optimization of power costs. Each manufacturer and supplier should be responsible both for their own balance sheet and for the imbalance of power, i.e. deviations from the contractual schedule of production or consumption.

By concluding bilateral contracts or buying power on the day-ahead market, power suppliers and producers are obliged to ensure their consumption and production at certain hours at the appropriate level. At the same time, they are parties that are responsible for the balance personally (or are included on a contractual basis in a certain balancing group).

In Ukraine, about 200 mining and metallurgical enterprises represent basic consumers of power. These types of enterprises have been operating in power market conditions for more than 3 years [64]. To switch to this format, power enterprises-consumers had to perform a significant amount of work to improve reporting forms of the automated power accounting system and update their energy services.

Until January 2019, at industrial enterprises, including mining ones, three-zone tariffs were used – "peak", "half-peak" and "night". The cost of power, for example, in April 2019 in the "peak" zone was UAH 2.94, in the "half-peak" zone – UAH 1.67, in the "night" zone – UAH 0.41. Enterprises had the opportunity to effectively adjust operation of drainage and hoisting at night, so they saved money on power costs due to the difference of more than seven times the cost of the peak and night zones. This had a positive impact on operation of power producing companies due to the unloading of peak zones, since energy-intensive consumers almost did not work in these zones.

With transition to the energy market, hourly tariffs began to operate, which are in fact two-zone tariffs – "day" and "night", differing from each other by almost half. For example, in April 2020, the cost in the "day" zone was UAH 2.05, in the "night" zone – UAH 0.96. Now enterprises do not use pauses in the morning and evening peak hours, so the load during these hours for energy companies increases.

If earlier power tariffs for enterprises were constantly and steadily only growing, now the market determines the levels of power costs. Therefore, it is expected that when the market in Ukraine will become reliable, it will have a positive impact on both energy companies and power consumers. However, to achieve such parity, it is necessary to approach the problem carefully from both sides based on the results of scientific researches.

At the same time, it should be remembered that the base-forming component of variability and energy-saving of both generating systems and consumers of power are forms of curves of power consumption [34, 37, 39, 66]. These curves can be daily, monthly, seasonal and yearly. The corresponding curves of generating systems depend on the trajectory of curves of power consumption by energy-intensive enterprises, therefore they can be adjusted in approximation to their optimal. As established [38, 41, 42], iron ore mining enterprises are noted for the greatest fluctuations compared to other industrial enterprises.

This dynamics of fluctuations is especially inherent in the daily curves of power consumption. Taking into account that according to the Law of Ukraine [64], tariffs for power consumption are determined by the energy market hourly for the day ahead, the problem of improving energy efficiency of mining enterprises (as well as other types of consumers) should be solved in this very perspective.

Along with the above arguments according to the state and prospects of Ukraine's energy sector in general and the power industry in particular, one should mention such a system-forming fact of our time as reliability and uninterrupted functioning of power supply systems of industrial enterprises and enterprises of housing and communal services of the state in extreme situations. This requires specific measures to be found, substantiated and developed in order to ensure stability and continuity of operation of power supply systems, including autonomous (backup) systems for generating power at enterprises, places of residence, etc.

1.3. Analysis of the current state of power supply and consumption by mining enterprises with underground methods of iron ore mining[1]

As noted in the previous section of this research, iron ore mining enterprises in general and those practicing underground methods of mining in particular are intensive consumers of power. For example, monthly volumes of power consumed by underground mines of national mining enterprises amount to about 22-26 million kWh. In this regard, these types of iron ore mining enterprises, by the way, like all other mining enterprises, are consumers who, along with other energy-intensive industries, determine volumes of power, power consumption curves and the degree of impact on the quality of power in power supply networks.

With regard to internal power systems (Fig. 1.1) of mining enterprises, here, among others, the criterion of the required level of continuity and reliability of power supply dominates, since the majority of power consumers of these enterprises, belong to the 1st category according to the need to ensure reliability of power supply [66].

Among the 1st category power consumers, ensuring reliability, safety and efficiency of the mining enterprise, the so-called stationary facilities (complexes) are of primary importance. These power consumers are characterized by complex structures and a significant level of energy intensity (they account for more than 80% of all power consumed by these types of mining enterprises).

Stationary installations are complexes with complicated energy-mechanical equipment designed for hoisting minerals and waste rocks to the

[1] When structuring the content of the section, the results of experimental studies obtained as directly by the author were used, such as those that were accumulated during a large scientific search in 1999-2021 at operating iron ore underground mines of Ukraine and which were kindly provided to the author for their further formatting by members of the scientific school under the guidance of DSc. (Engineering), Professor Sinchuk.

surface (skip hoists), lifting and lowering people, materials, equipment (cage lifting installations); pumping water from underground mine workings to the surface (water drainage facilities); artificial ventilation of mine workings and creation of normal atmospheric conditions for miners (main ventilation fans); production of pneumatic energy – compressed air energy used in operation of mining combines, jackhammers and drilling hammers, winches (compressor units), local ventilation fans, pumps, etc. Stationary installations form the levels and modes of total consumption of power by iron ore mining enterprises.

As can be seen from Table 1.1, consumption of this type of energy at individual iron ore underground mines differ from each other. It depends on many factors, including the volume of iron ore production, operating depths of mining, groundwater inflow, the system of underground levels, etc. [67].

Table 1.1 shows data on the specific power consumption of individual iron ore underground mines. The data presented confirm the preliminary conclusion.

In the modern format of functioning of mining enterprises, to form the cost of iron ore production and corresponding applications for the energy market of Ukraine, according to existing methods, iron ore enterprises determine control figures for their structural units for daily and hourly levels of power consumption.

Table 1.1 – Power consumption and costs of Ukraine's iron ore underground mines (December 2020)

Underground mines	Power consumption, thousand kWh	Percentage of power consumption, %	Amount of payment for power, thousand UAH	Percentage of payment for power, %	Specific cost, UAH/ kWh
Oktiabrska (Kryvyi Rih)	3871.095	14.40	3510.437	13.04	0.90683
Rodina (Kryvyi Rih)	6014.121	22.38	5541.670	20.59	0.92144
Hvardiiska (Kryvyi Rih)	3919.249	14.58	4263.806	15.84	1.08791
Ternivska (Kryvyi Rih)	3522.988	13.11	3291.708	12.23	0.93435
named after Frunze (Kryvyi Rih)	4104.824	15.27	4620.472	14.81	1.12562

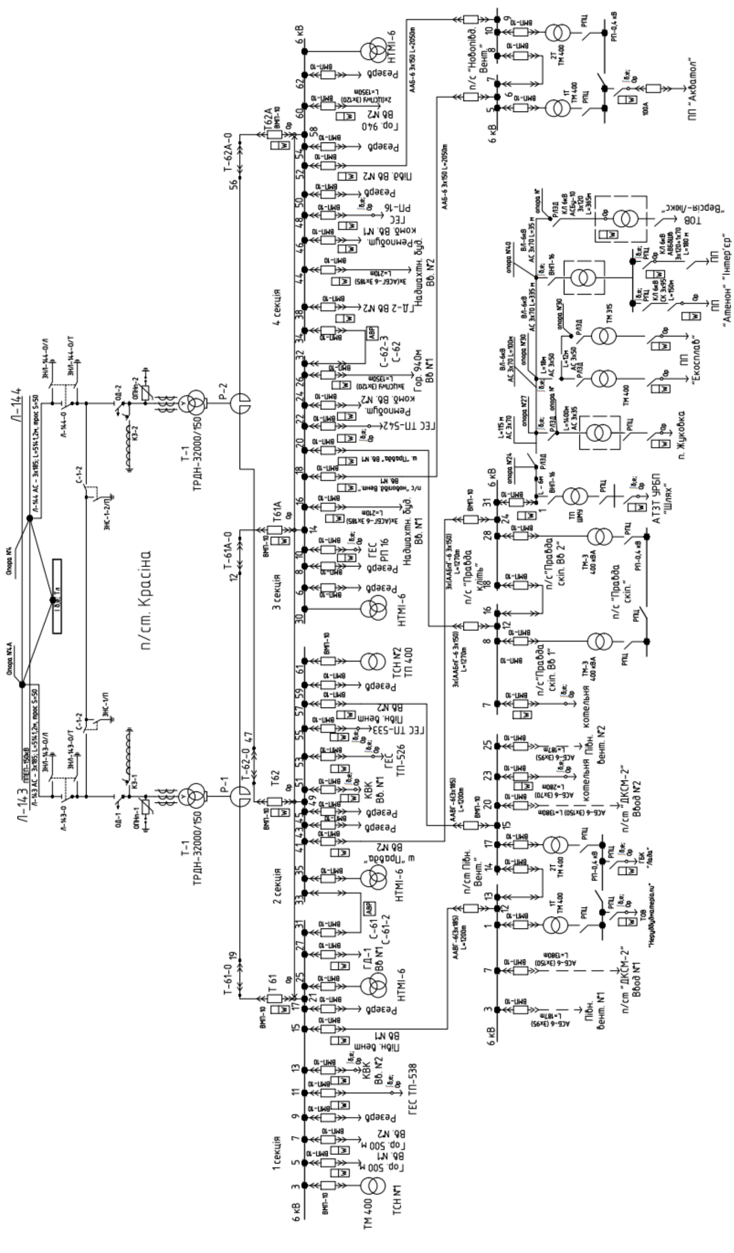
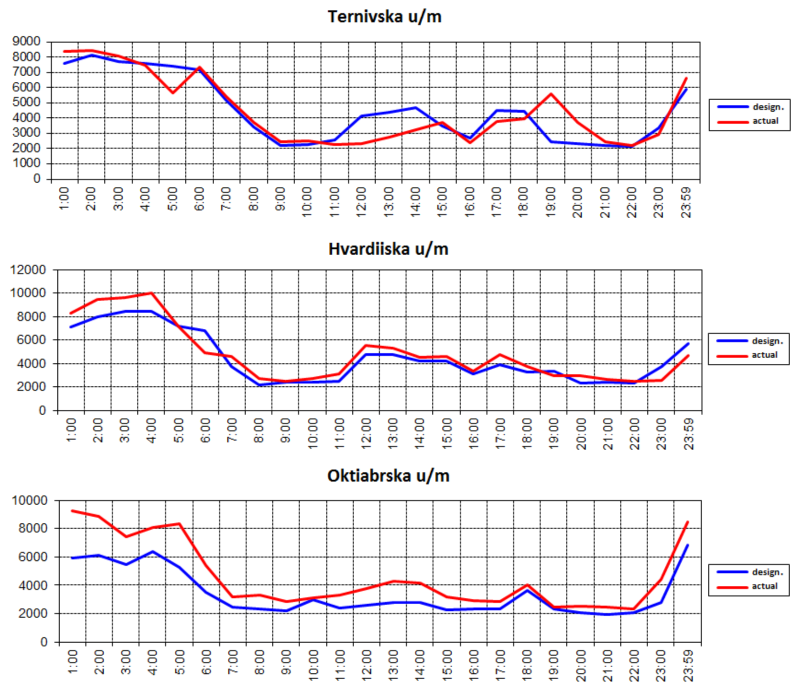


Figure 1.1 – Internal power supply systems of iron ore underground mines

Yuvileina (Kryvyi Rih)	5073.224	15.12	4793.081	14.62	0.94478
named after Artem (Kryvyi Rih)	4576.334	16.78	4510.298	14.95	0.98557
Hyhant-Hlyboka (abandoned) (Kryvyi Rih)	3376.675	89.23	3844.850	88.45	1.13865
Ekspluatatsiina (Dniprorudne)	3567.732	14.94	3729.671	13.64	1.04539

Conclusions from "designed-actual" curves (Fig. 1.2) of power consumption vary. At the same time, inconsistency for each mine is individual, but the increase in both designed and actual levels of power consumption is stable both at night and during the day.

Fig. 1.2 presents designed and actual power consumption of individual national iron ore underground mines.



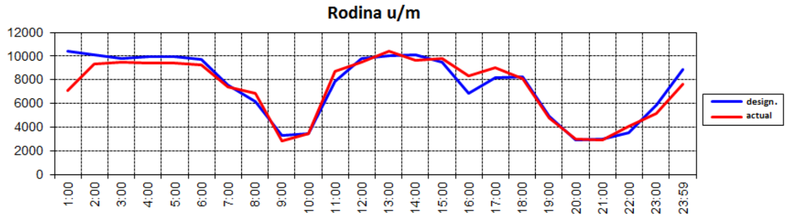


Figure 1.2 – Designed and actual consumption of active power at some iron ore underground mines of Ukraine (September 25, 2020)

Nevertheless, for further analysis, it is interesting to consider differentiated assessment of power consumption at iron ore underground mines by type of consumers.

Fig. 1.3 shows average distribution of power among structural units of national iron ore underground mines (without considering compressor units of the power shop).

As can be seen from the above diagram, total power consumption of skip hoists, water drainage and ventilation facilities is more than 90 %.[2]

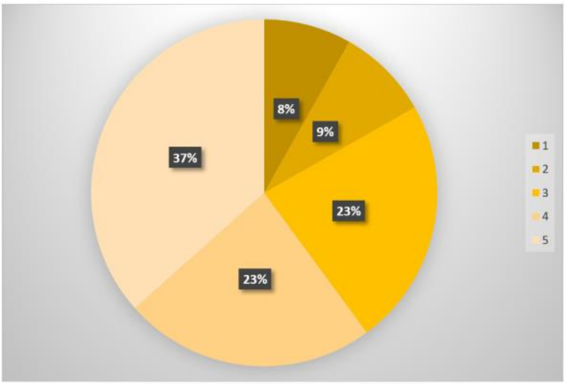


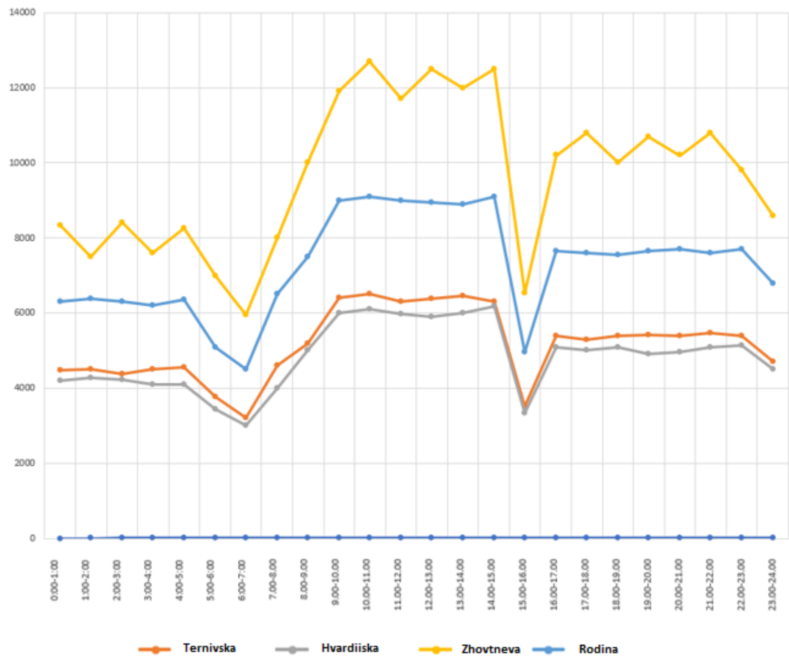
Figure 1.3 – Distribution of power consumption among energy-intensive consumers of iron ore underground mines, averaged for 2016-2021:
1 – others; 2 – crushing and sorting plant; 3 – ventilation; 4 – skip hoisting;
5 – water drainage

Other consumers include surface and underground consumers (cage lifting units, compressor units, dispensers, crushers, electric trains).[2]

[2] The above diagram does not take into account power consumption of powerful compressor stations that constitute a separate structural unit – a power shop, and each compressor station can serve 1-3 underground mines with compressed air.

Levels of power consumption of the above-mentioned energy-intensive consumers vary for each individual underground mine (Fig. 1.4).

This is the result of the fact that the mode of power consumption by individual stationary facilities is affected by specific technological features of a particular iron ore underground mine [12, 22, 23, 67]. This situation makes it impossible to form a single generalized algorithm for controlling power consumption modes for all subjects (underground mines). This thesis also applies to those mines that are united into a single technological structure of integrated works, concerns, etc., and this should be taken into account when developing an algorithm for controlling power consumption of a particular underground mine.



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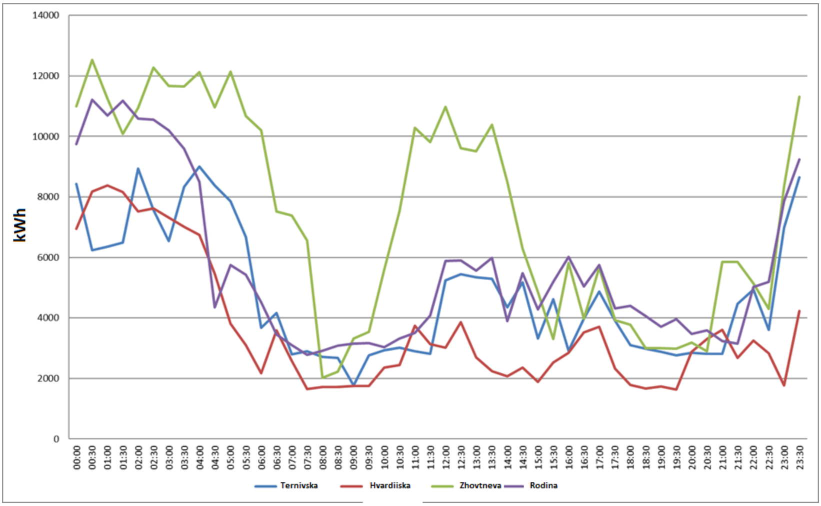
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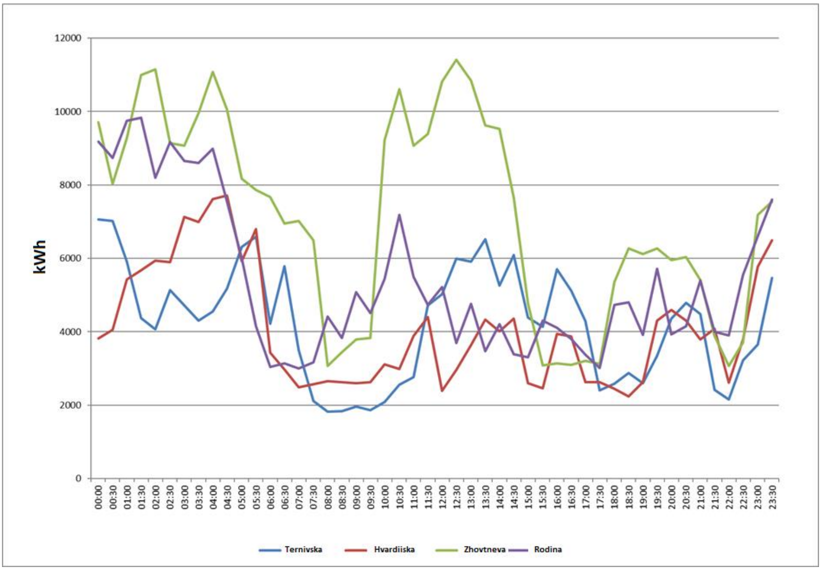
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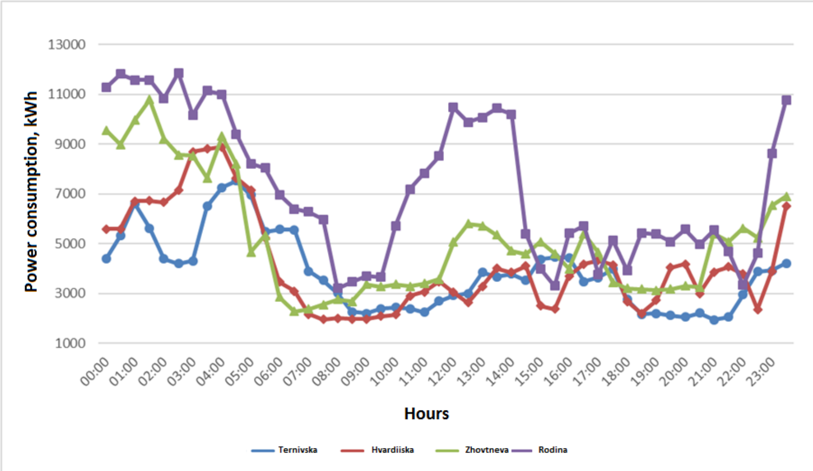

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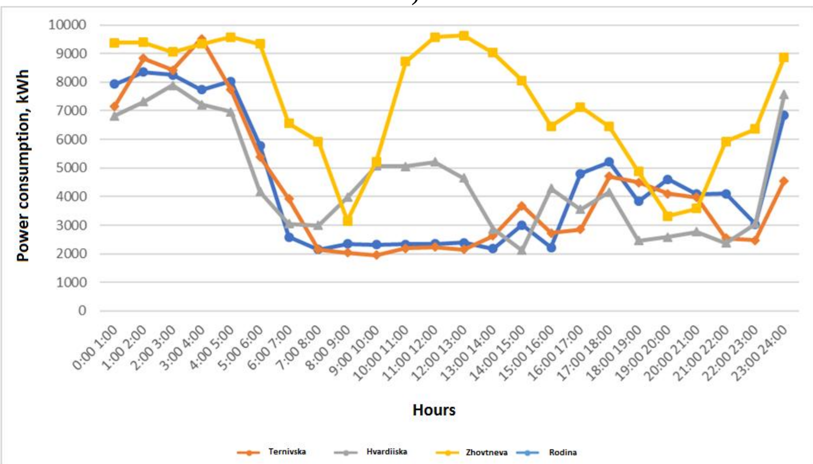

e)

Figure 1.4 – Power consumption by a number of iron ore underground mines of Kryvyi Rih iron ore basin: a) April 23, 1999; b) April 23, 2012; c) April 23, 2013; d) April 23, 2015; e) April 23, 2020

As is known, until 2019, national underground mines, as well as other types of industrial enterprises, used a three-zone tariff for payments for power consumed, this fact urging them to operate maximum hours at night and reduce power consumption in peak hours – in the morning and in the evening. Since such a mode was acceptable under technological conditions, both the enterprise and the power supplying company benefited: the industrial enterprise spent less money on power and the power supplying company had a more stable schedule of power consumption due to compensation for the increase in power by city power grids during peak hours.

In 2019, transition to energy market conditions and introduction of floating hourly tariffs led to reduction of the operating time during off-peak hours, and this, in turn, reduced irregularity of power consumption supplied by energy companies. Fig. 1.5 – 1.12 show daily curves of power consumption for skip hoists, crushing and sorting plants (CSP), ventilation and water drainage facilities of four iron ore underground mines before and after introduction of the energy market.

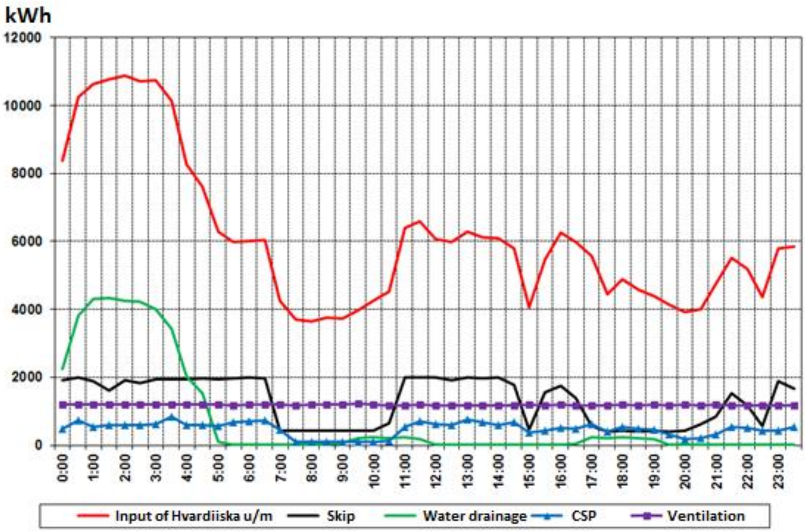

Figure 1.5 – Daily curves of power consumption of Hvardiiska u/m (Kryvyi Rih) in November 25, 2018 (before introduction of the energy market)

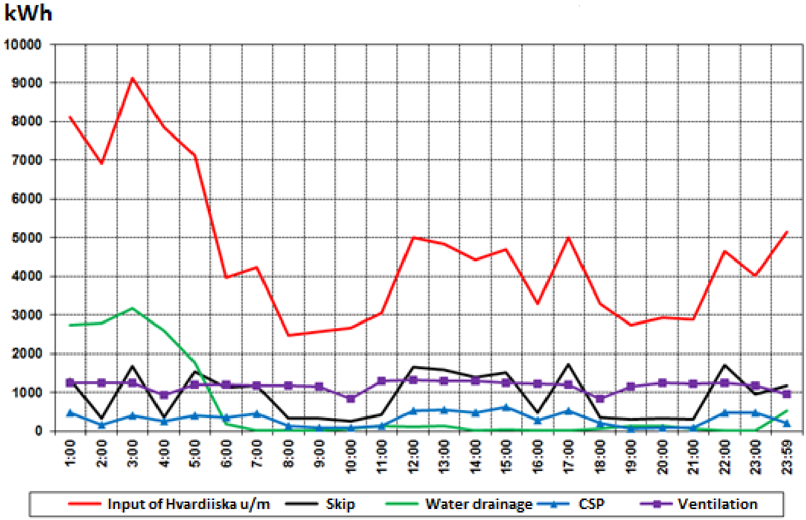

Figure 1.6 – Daily curves of power consumption of Hvardiyska u/m (Kryvyi Rih) in October 8, 2019 (after introduction of the energy market)

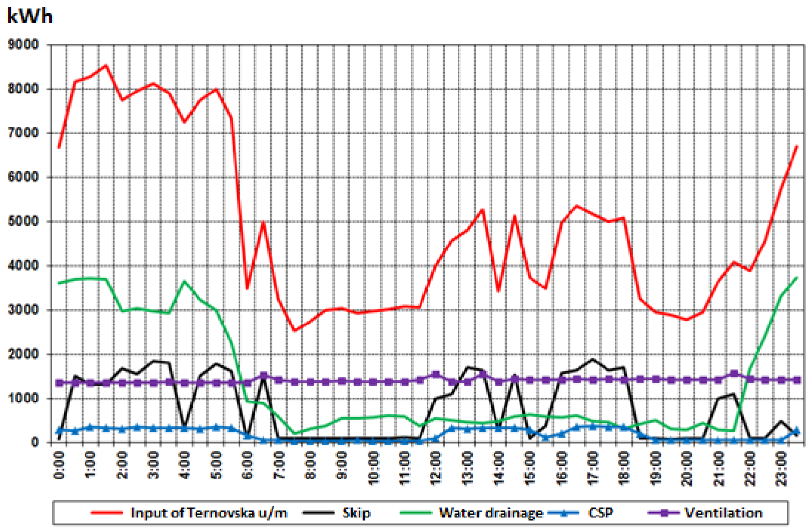

Figure 1.7 – Daily curves of power consumption of Ternivska u/m (Kryvyi Rih) in November 25, 2018 (before introduction of the energy market)

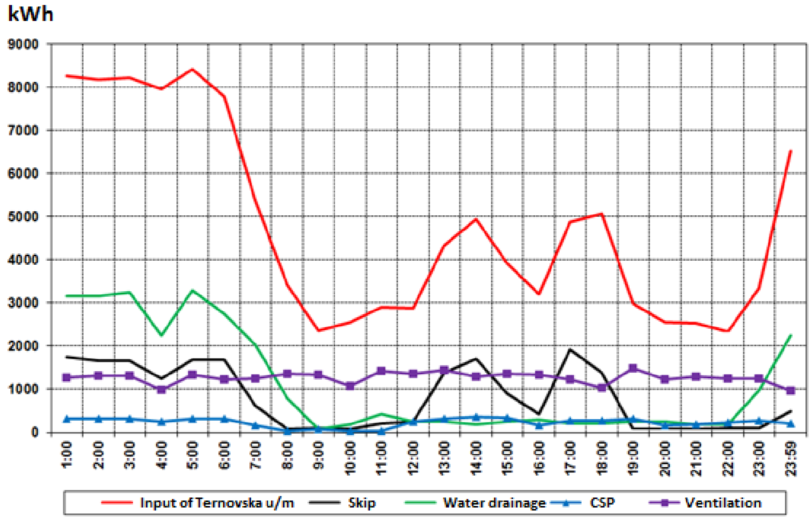

Figure 1.5 – Daily curves of power consumption of Ternivska u/m (Kryvyi Rih) in October 8, 2019 (after introduction of the energy market)

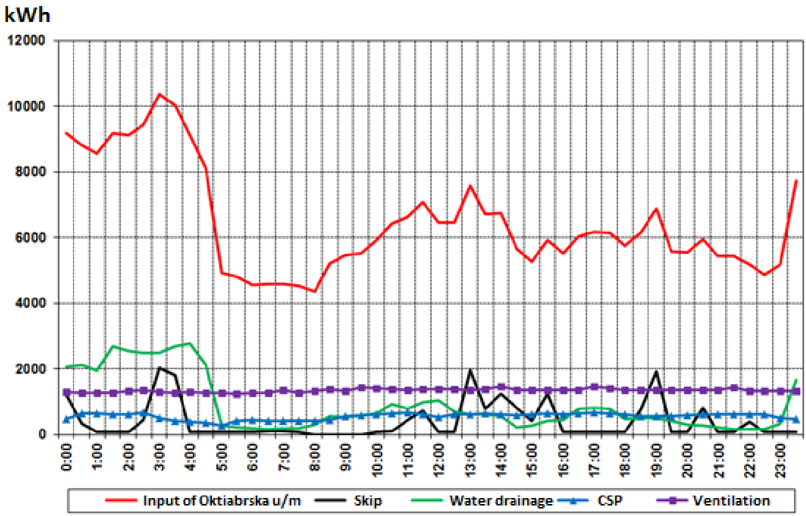

Figure 1.9 – Daily curves of power consumption of Oktiabrska u/m (Kryvyi Rih) in November 25, 2018 (before introduction of the energy market)

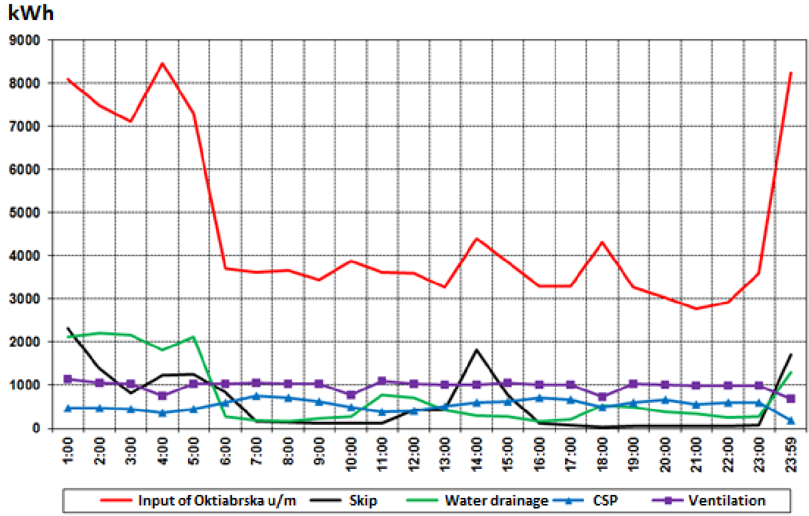

Figure 1.10 – Daily curves of power consumption of Oktiabrska u/m (Kryvyi Rih) in October 8, 2019 (before introduction of the energy market)

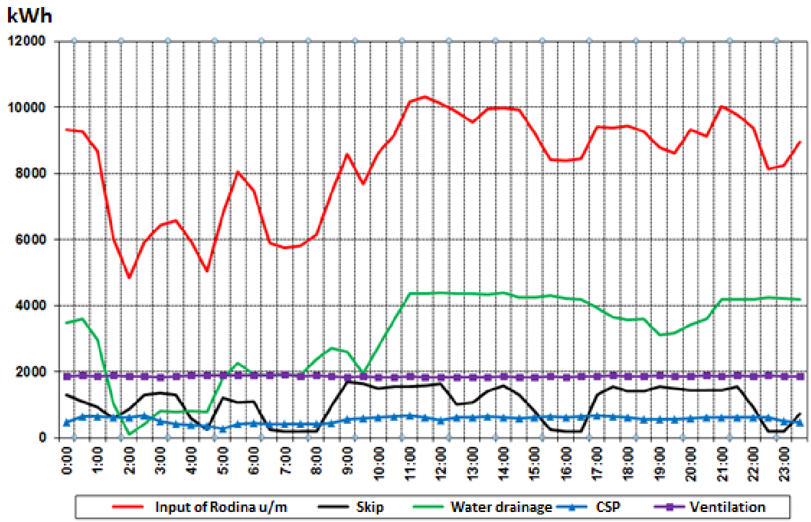

Figure 1.11 – Daily curves of power consumption of Rodina u/m (Kryvyi Rih) in November 25, 2018 (before introduction of the energy market)

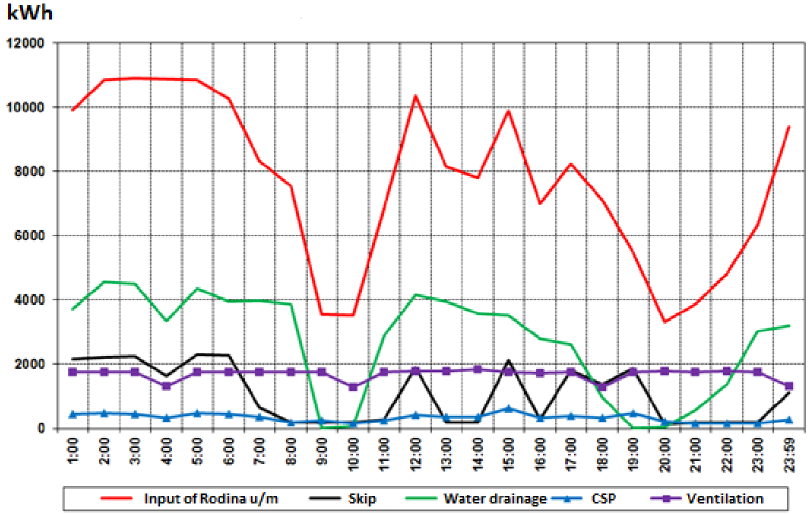

Figure 1.12 – Daily curves of power consumption of Rodina u/m (Kryvyi Rih) in October 8, 2019 (after introduction of the energy market)

Analysis of the curves shown that those for 2018 have a discreteness of 30 minutes, while those for 2019 – 1 hour. Because of this, the curves of 2018 are more informative and show more accurately dynamics of changes in power consumption over time. Also, in the curves for 2019, one can observe a decrease in power consumption levels of all consumers.

Analysis of power consumption of Hvardiiska underground mine (Kryvyi Rih) shows that in 2019 there was a decrease in power consumption levels for a number of consumers, including water drainage facilities due to optimization of electrical equipment of stationary installations.

In 2018, water drainage installations operated at night from 0:30 to 4:30, and in 2019 – from 23:00 to 5:30. Such an increase in the period of pumping mine water due to the number of running pumps reduces the maximum amplitudes of power consumption at night, which limits voltage fluctuations of the mine power grid.

The above curves allow concluding that both the levels of consumption and dynamics of the curves of total power consumption by the underground mine from the power supply grid are determined by consumption dynamics of mine skip hoisting and mine water drainage facilities.

Moreover, the natural process of constant deepening of iron ore underground mines leads to an increase in power consumption by these consumers, which is caused by an increase in the distance of hoisting of raw materials and mine waters to the surface, a change in mining and geological conditions (mining of deeper levels, the length of transport workings, etc.), all this entailing increased power costs.

This once again emphasizes the relevance of researching into the process of power supply and consumption of these types of enterprises with subsequent conclusions adding more economic relevance to this process.

1.4. Analysis of technological and power parameters in water drainage from mine workings of iron ore underground mines

As indicated in 1.2 of this research, water drainage is noted for one of the largest levels of power consumption at iron ore underground mines.

Water drainage from mine workings is carried out by special equipment – water drainage facilities (installations) [68, 69].

Depending on the depth of an underground mine and the number of levels to be mined, two main hydraulic schemes of the main water drainage complex are possible – direct pumping of water to the surface and a stepped scheme with pumping water from the lower level to the upper one [70-77]. With such a stepped scheme, pumps of each mine level operate independently of each other (Fig. 1.13).

In some conditions, another stepped scheme of the main drainage system may be advisable, in which the pump of the above level is connected literally to the lower pump (Fig. 1.14). In the vast majority of cases, pumps in pumping chambers are placed above the water level in water tanks, although sometimes they are located below this level.

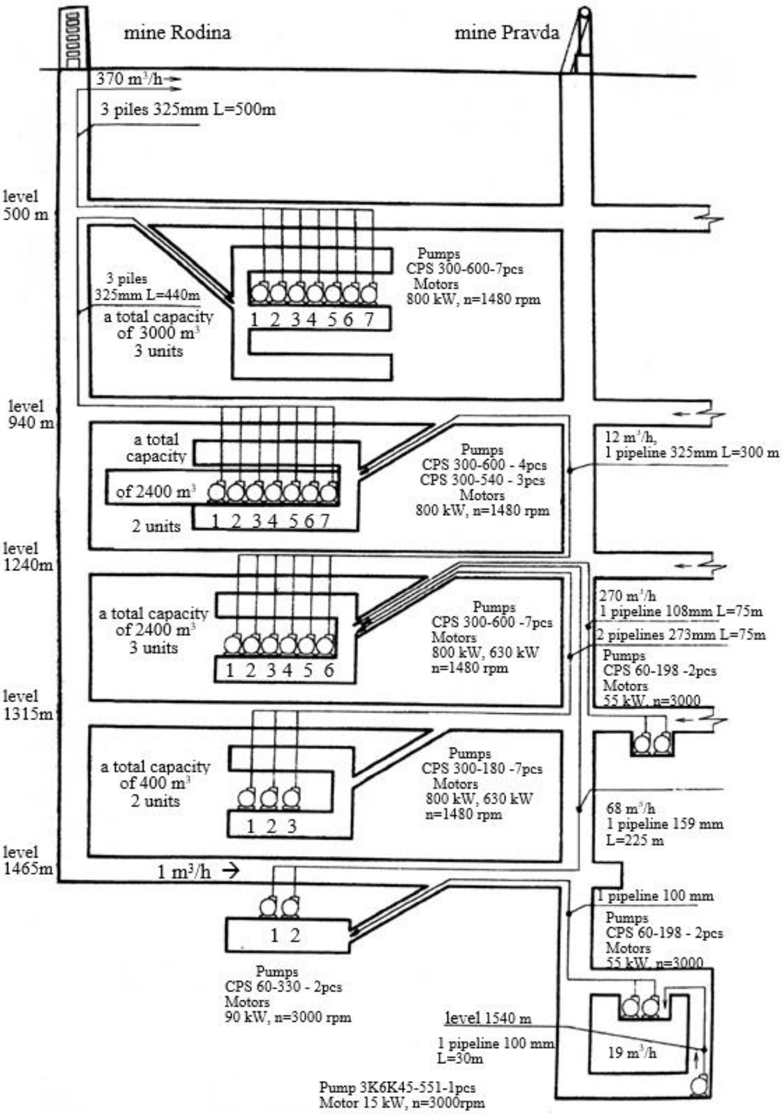

Figure 1.13 – Water pumping by water drainage facilities of the integrated water drainage complex of Rodina and Pravda underground mines (Kryvyi Rih)

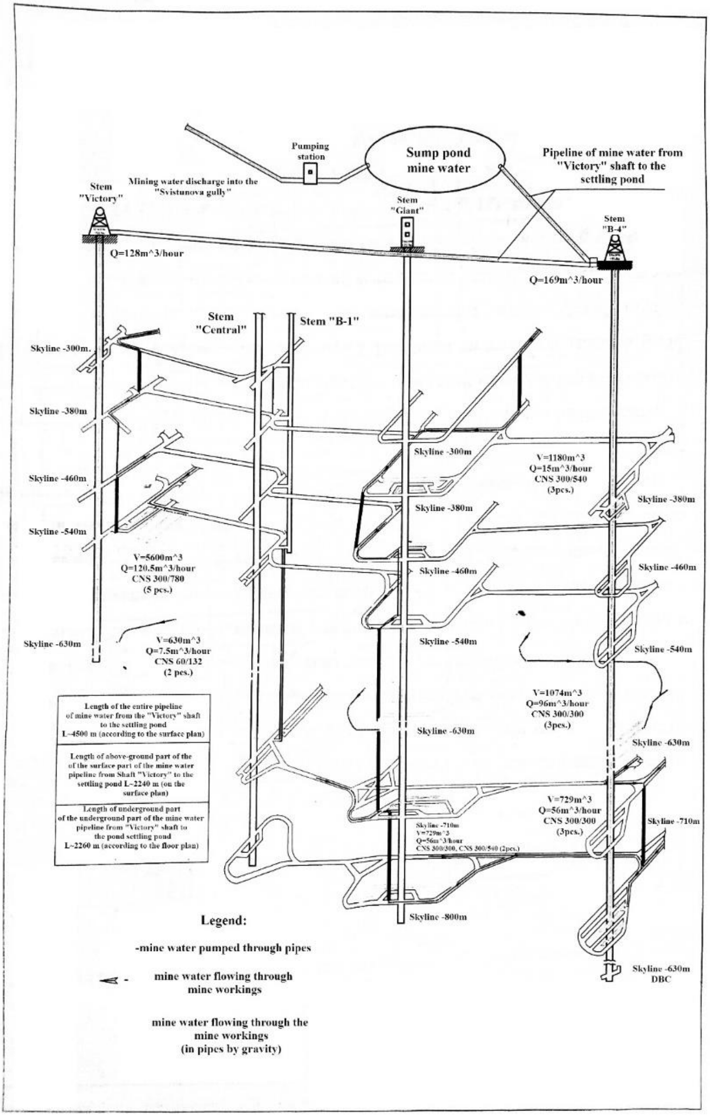

Figure 1.14 – Water pumping by water drainage facilitiess of the abandoned Hihant-Hlyboka underground mine (Kryvyi Rih)

Table 1.2 and Annex A provide data on daily power consumption of water drainage complexes of iron ore underground mines.

Table 1.2 – Daily power consumption by water drainage facilities of iron ore underground mines of Ukraine

Unaderground mines	Добова електроенергія, кВт·год		
	День	Ніч	Всього
Oktiabrska (Kryvyi Rih)	41091	34030	75121
Rodina (Kryvyi Rih)	13712	14215	27927
Hvardiiska (Kryvyi Rih)	1458	25537	26995
Ternivska (Kryvyi Rih)	13446	17322	30768
named after Frunze (Kryvyi Rih)	2407	15247	17654
Yuvileina (Kryvyi Rih)	6884	24405	31289
named after Artem (Kryvyi Rih)	5832	17496	23328
Hihant-Hlyboka (abandoned) (Kryvyi Rih)	15967	29653	45620
Ekspluatatsiina (Dniproprudne)	7221	37884	45105

Analysis of the data in Table 1.2 shows that specific power consumption for water drainage varies in the range of 6.2 - 7.2 kWh/m.

Underground mines that are abandoned or decommissioned and provide pumping of mine water to prevent flooding also consume power for water drainage facilities. Hihant-Hlyboka underground mine is one of such mines with power consumption curves shown in Fig. 1.15. The average daily power consumption of Hihant-Hlyboka underground mine makes from 43200 to 55000 kWh, which results in daily water flow from 6170 to 7800 m^3. You can see that water drainage occurs both at night and in the daytime. Fluctuations in power consumption are affected by disturbances associated with operation of cage hoisting.

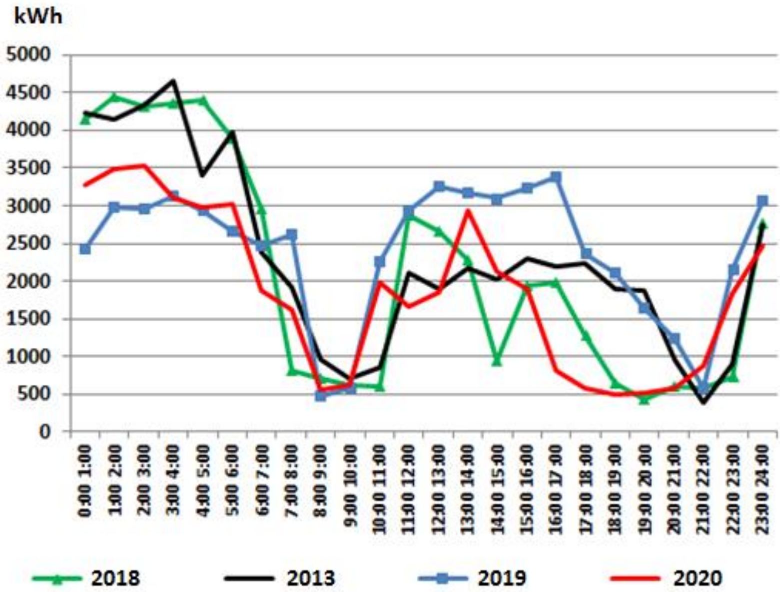

Figure 1.15 – Daily curves of power consumption of the abandoned Hihant-Hlyboka underground mine (Kryvyi Rih) in 2013-2020

As can be seen from the curves, from year to year there is a certain synchronicity of daily fluctuations in power consumption levels. This once again emphasizes the potential of controlling this process in the "consumer-regulator" mode.

If for a non-operating mine the problem of energy efficiency of water drainage is one-vector in its solution (hours of the day without considering other technological impact factors in the time function of underground mining operations), operating underground mines face a multi-vector task involving uncertainty and instability of a number of input parameters.

Meanwhile, the entire technological synthesis of water drainage systems of both "operating" and "non-operating" underground mines functions within a single hydropower structure.

Table 1.3 provides data on water drainage a number of iron ore underground mines in Ukraine.

Table 1.3 – Characteristics of water mine drainage

Underground mines	Daily water flow, m^3	Specific water flow, m^3/h	Tank capacity, m^3
Rodina (Kryvyi Rih)	11429	476	26600
Oktiabrska (Kryvyi Rih)	3112	129	20080
Hvardiiska (Kryvyi Rih)	3410	142	15000
Ternivska (Kryvyi Rih)	4392	183	15548
Named after Frunze (Kryvyi Rih)	2520	105	12890
Yuvileina (Kryvyi Rih)	4670	195	16780
Named after Artem (Kryvyi Rih)	3240	135	15660
Hihant-Hlyboka (abandoned) (Kryvyi Rih)	7128	297	21375
Ekspluatatsiina (Dniproprudne)	6537	272	15784

As can be seen from the above, the greatest water flow occurs at Rodina underground mine due to complicated mining and geological conditions. Table 1.4 provides information on main underground levels where water drainage facilities are located and the number of pumps on these levels.

This leads to the need not to return all the pumped water to deep mine levels during power generation, but to accumulate it in the corresponding tanks on the first levels (500 m, 437 m, 472 m, 527 m). This will allow you to discharge all the water in the daytime.

Table 1.4 – Underground levels and mine pumps

Underground mines	Levels (m) / number of pumps
Rodina (Kryvyi Rih)	500/7; 940/7; 1240/6; 1465/6
Oktiabrska (Kryvyi Rih)	437/4; 965/4; 1115/4; 1265/4
Hvardiiska (Kryvyi Rih)	472/5; 792/4; 1190/4; 1350/3
Ternivska (Kryvyi Rih)	527/5; 1050/4; 1200/4; 1350/4
named after Frunze (Kryvyi Rih)	410/3; 910/3; 1060/4; 1135/2
Yuvileina (Kryvyi Rih)	480/5; 940/5; 1340/5
named after Artem (Kryvyi Rih)	475/6; 865/8; 1045/5; 1135/9
Hihant-Hlyboka (abandoned) (Kryvyi Rih)	380/3; 540/5; 630/2; 710/2; 800/3
Ekspluatatsiina (Dniproprudne)	400/10; 480/7; 640/8; 840/5; 940/3; 1040/3

To analyze parameters of water drainage functioning at underground mines, the coefficient of water flow is determined, which is the ratio of the annual inflow (m^3) to the volume of the annual water flow of an iron ore underground mine (Fig. 1.16).

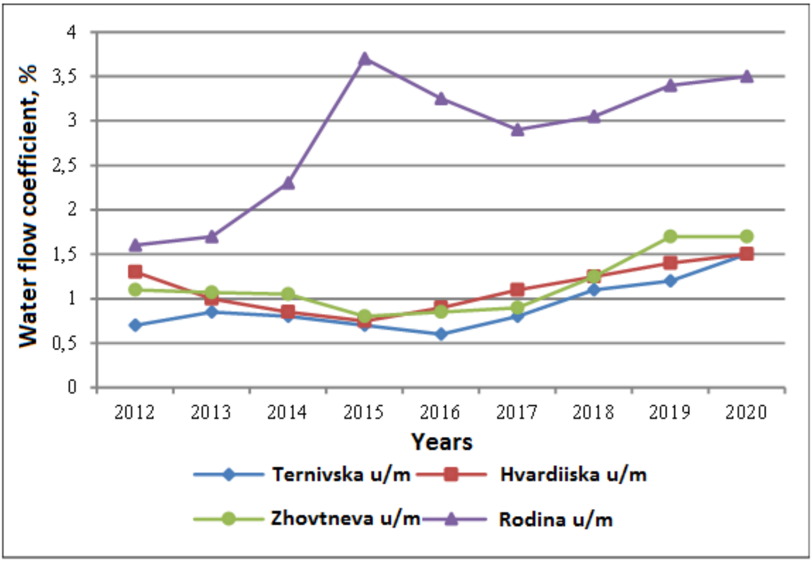

Figure 1.16 – Water flow coefficient of some iron ore underground mines of Kryvyi Rih iron ore basin

For water drainage facilities, centrifugal pumps (CNS) of the ring-section design are used. Table 1.5 shows specifications of mine centrifugal pumps.

Table 1.5 – Specifications of pumps for water drainage from underground mine levels of national iron ore nderground mines

Specifications	Pump size		
	CNS 300-480	CNS 300-600	CNS 300-800
Water flow, m^3/h	300	300	300
Pressure, m	480	600	800
Motor type	A4-450X-4M	A4-450X-4M	A-13-46-4A
Motor power, kW	630	800	800
Rotational speed, rpm	1475	1475	1450
Rated voltage, kV	6	6	6

Figures 1.17 – 1.20 show curves of power consumption of water drainage facilities of various underground levels of some underground mines.

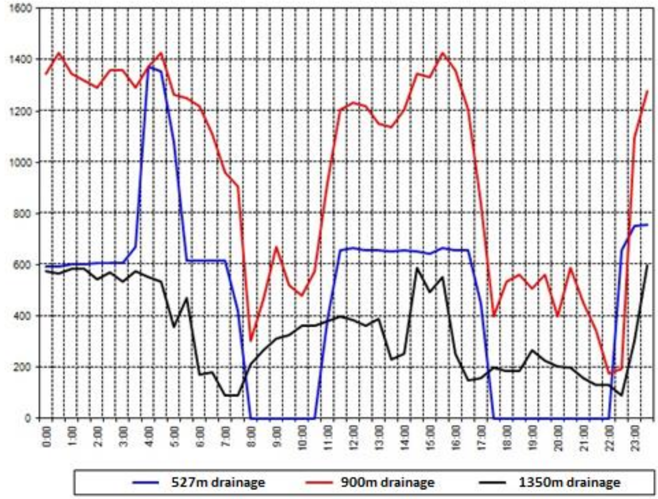

Figure 1.17 – Curves of active power consumption by electric drives of mine water drainage facilities of Ternivska underground mine (Kryvyi Rih)

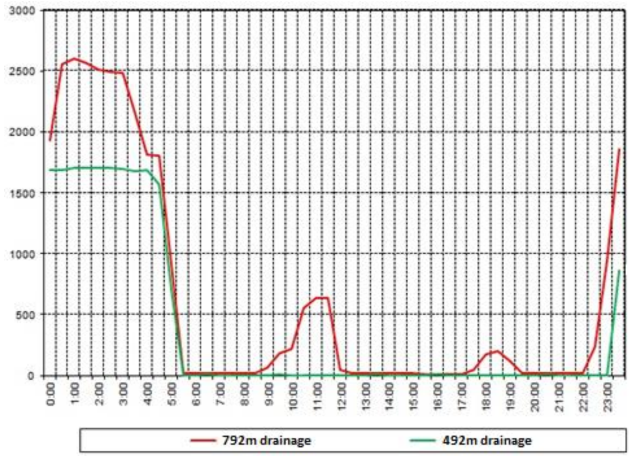

Figure 1.17 – Curves of active power consumption by electric drives of mine water drainage facilities of Hvardiiska underground mine (Kryvyi Rih)

Figure 1.17 – Curves of active power consumption by electric drives of mine water drainage facilities of Rodina underground mine (Kryvyi Rih)

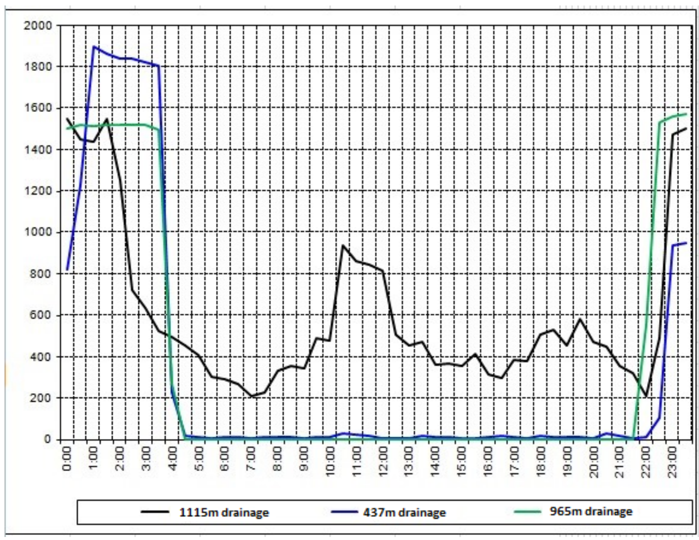

Figure 1.17 – Curves of active power consumption by electric drives of mine water drainage facilities of Oktiabrska underground mine (Kryvyi Rih)

The curves indicate that pumps are turned on for pumping mine water mainly at night, when the cost of power is minimal. When the pumps do not have time to pump the water out completely, they can operate during the daytime.

Since other consumers work on busbar sections of substations in parallel with the pumps, they contribute to the process of disturbing power consumption curves of these levels.

1.5. Analysis of scientific achievements to solve the problem of increasing energy efficiency of mine water drainage facilities

The need to solve the problem of increasing energy efficiency of mine water drainage facilities arose and became the priority with the first steps to create electromechanical complexes for this process [78-79]. Yet, chronologically, the search, as well as "geography" of ways to achieve positive results, has changed. Thus, since the 50s of the last century, the emphasis of research has been placed on creating the ACS for pumps of main water drainage facilities. At the same time, the level of technological implementation corresponded, and even now corresponds, to the state of the electrical and electromechanical element base for the current research.

It was in this perspective that the first attampts were based on systems for smooth (non-rheostat) regulation of frequency of drive revolutions of mostly asynchronous electric motors of water pumps. In their essence, these studies were subsequently formatted into the option of switching main water dranage facilities from the "consumer" power mode to the "consumer-regulator" one. Certain positive achievements have been achieved [80-90]. As for the above aspect, we note that in the logistics of the subsequent research stages, this component was and is a starting necessity in the range of its varieties aimed at increasing energy efficiency of main water drainage facilities.

This research line receives a new breath with the advent of high-speed modern methods of computer modeling applied to functioning of electromechanical complexes of water drainage facilities in order to search for efficient modes of their operation.

The focus of domestic researchers in the field of transferring operation modes of the main water drainage facilities from the "consumer" power mode to the "consumer-regulator" one became relevant more than 40 years ago, and this despite the fact that at that time the problem of energy efficiency was not yet a priority task for increasing efficiency of main water drainage facilities. According to this "yesterday's" vision, at that time the problem was solved purely as the need to make operation modes of main water drainage facilities automatic. At the same time, the criterion for changing operation modes was fullness of the main underground tank.

Among a wide range of studies in this line, those by S.A. Volotkovsky, V.N. Herasymovich, V.H. Zaika, H.H. Pivniak, A.V. Prahovnyk, Y.T. Razumnyi, V.P. Rozen, O.M. Sinchuk, and O.V. Stohnii provide some positive results to be implemented. These issues were also investigated into by S.P. Shevchuk, H.I. Danylchuk, V.F. Nakhodov and a number of other scientists [34, 37, 57, 59, 91-107]. Subsequently, as an option for equalizing daily load curves of coal underground mines by changing operating modes of energy-intensive consumers, including main water drainage facilities, these issues were considered by V.I. Hordeiev, S.P. Denisyuk, Yu.H. Kachan, O.V. Kyrylenko, P.D. Lezhnyuk, O.V. Liakhomskyi, V.P. Rozen, V.I. Khromusov, Ye.N. Chervonyi, V.V. Shchutskyi [15, 19, 39, 42, 43, 46, 59, 61, 62] and a number of other researchers.

However, we note that the researches of the above-mentioned scientists were based on coal underground mines with their technological specifics of extracting this type of minerals and, accordingly, this water drainage process.

Unfortunately, in the future, the relevance of these studies was reduced to zero due to the "human factor" existing at that time, when the energy component in the cost of mineral mining was not so significant.

As a compensation for this fact, there were studies in solving the problem of automatic control of the water drainage facilities of iron ore underground mines by a group of scientists from Kryvyi Rih National University [22, 89, 96]. At the same time, it should be noted that these studies analyzed the local solution to the problem in the "include- exclude" format at certain hours of the day. A method to reduce the levels of payment for the consumed power by changing the time of the daily curves of main water drainage was designed for solving the problem of energy efficiency by transferring the maximum operation of these complexes to the economical (night) hours of the day. While a certain saving of material resources really took place, there was an excess of power consumption in other periods – off-peak hours of the day. That is, the actual savings for the consumed power during peak hours were minimized by an increase in consumption levels during off-peak periods of the day.

At the end of the 20th century, the boundaries of scientific research in Ukraine as to improving energy efficiency of main water drainage complexes were expanded.

In fact, the whole range of these fruitful studies has been reduced to a single global solution: the transfer of electromechanical complexes of main water drainage facilities from the "consumer-regulator" mode to the "consumer-regulator-generator" power mode.

Other researches were also built in this area. Thus, in [103], the original integrated model of a coal mining enterprise is given to evaluate and maintain effective energy-saving solutions. It is proposed to consider an enterprise as an integrated energy consumption object, to format the water drainage process in the form of a model of connected instances of four corresponding subsystems. The solution of such an integrated model provides synchronism of the operation of subsystems to control the general automated control system of the power consumption levels of the enterprise as a whole. However, based on the analysis of the research material, in the structure of the proposed system there is no differentiation of the levels of influence of energy-intensive consumers on total consumption of the enterprise, and the recommended project of controlling subsystems reflects only certain components of the technology of underground mineral production. This approach averages specific features of functioning of power consumers, and does not allow realizing the energy potential of main water drainage facilities.

In applying just such an expectedly effective approach, studies were conducted for gold mining enterprises [108]. Here, the authors directed their search to reduce power consumption by all energy-intensive consumers of the enterprise, including pumps for main water drainage facilities.

Conducting further analysis of the results of solving the problem, we note that in recent years, the idea of creating pump-storage power plants (PSPP) on the basis of water drainage facilities of mining enterprises has come to the fore.

For the first time the idea of using mines as basic structures for the constructing PSPPs dates back to 1960 [109]. However, this idea was not specific in the logistics of the project, so never implemented.

Subsequently, in 1975, the first real experimental project of Mount Nore (in northern New Jersey) was developed, but its further promotion for long-term practical implementation did not occur [110].

[111] considers implementation of the project for a PSPP based on coal underground mines, which are decommissioned in the Asturian central coal basin (Spain). In the coming years, all coal underground mines in the region are planned to be closed. The network of mine tunnels in this region, which has been in operation for more than 200 years, comprises more than 30 underground mines and can accommodate 200.000 m^3 of water at depths

of 300m-600 m, this providing advantages for creating a PSPP there. Work in this research area continues.

[112, 113] note that pump-storage systems can be found worldwide. Yet, all of them are large-scale PSPPs. However, the demand for distributed generation systems based on renewable power sources has opened the market for a new generation of renewable energy facilities that can be created on a much smaller scale, but will be economically viable and environmentally acceptable as compared with their larger prototypes. The research presents and calculates the expected efficiency of PSPPs in functions of a number of basic technological parameters.

Such a search structure, or the one close to the analyzed ahead, is set out in [114-123]. Here, a set of criteria is formatted, which are recommended for practical implementation of a PSPP project. The value of this study lies in the fact that it outlines a range of solutions for future developments. The paper highlights an interesting fact that research conducted by the World Bank recognized that most of Africa's underground mines are located in areas with inadequate infrastructure regarding the centralized supply of power to them, and that it is these mines that can "cooperate with the authorities in building PSPPs on the basis of their own water drainage systems. In this way, they will be able to provide power not only for their own needs, but also for the population."

In Ukraine, creation of PSPPs based on water drainage facilities of underground mines has been actively analyzed in recent decades. The first results were obtained in [119, 122, 123].

Currently, national PSPPs provide about 1% of the total power production, while in a number of countries of the world this figure is more significant. Moreover, in the national energy programs of these states, the ways of solving the problem that is being analyzed are expanding annually, as well as the pace of their practical implementation, which is reflected in significant volumes of growth in power production by PSPPs. During the construction of a PSPP, as a rule, the natural potential (landscape) is used to the maximum.

Both in Ukraine and the world, underground mining enterprises are used to implement such projects. Thus, in Germany (North Rhine - Westphalia), the PSPP is created at one of the underground mines that is being preserved (Prosper - Haniel).

In this country, creation a PSPP on the basis of underground mines is initiated as an experiment that is financed primarily by public funds. Upon obtaining a positive effect, the experiment is planned to be turned into a segment of the national project for developing the state's energy complex.

Similar projects are implemented in Australia, Austria, South Africa, Spain, France and a number of other countries of the world [111, 112]. This area of scientific research is associated with the need to increase power production and replace outdated power plants with new types.

Preventive studies, mainly by foreign researchers, indicate that by 2050, the demand for power in the world will increase by 62%. At the same time, it is understood that a significant share of the growth of this demand will have to be ensured by power generation based on renewable energy sources.

Moreover, such a transformation in the structure of power production involves not only development of modern energy-efficient sources of power generation, but a new topic for the industry — a profitable and reliable technology for its accumulation. According to the research, in the near future, it is storage (accumulation) technologies that will play a leading role in the energy complex of states, which will allow renewable energy to become a major source in the energy sector [143].

According to [144], power accumulation should ensure its accumulation with the possibility of generation in the required volume in the required period of time. It is this potentially possible method of accumulation that underground pump-storage facilities based on main water drainage of underground mines can become. For this option, there are some positive aspects in Ukraine [145].

Thus, the Energy Strategy of the state focuses on development and implementation of domestic energy-intensive industries of autonomous power sources, which will operate on their own fuel and energy resources. Such enterprises are underground iron ore mines.

In Ukraine, over the past 50 years, development and extraction of minerals has been carried out at almost 50 underground mines. A significant number of them are actually closed and in the so-called conservation mode, the rest are functioning and, according to forecasts, will function for at least another 20-25 years. However, the problem of groundwater drainage remains constant for all, without exception underground mines.

In addition, when developing these projects, it should be understood that creation of PSPPs based on underground mines, or rather their water drainage systems, cannot ensure the functioning of the latter in a continuous mode. This is due to the fact that the water that is concentrated in the underground mines enters constantly and needs to be pumped into surface tanks. Water from these tanks is a source for hydrogeneration but only as a partial option. That is, at its core, an underground-mine-based PSPP can operate only in peak modes. Nevertheless, this option of obtaining power is very significant and has the right to exist. Therefore, the task of developing and justifying principles of PSPP construction based on underground mines is relevant and timely.

This thesis is gaining even greater relevance in the modern vision of the political situation in Ukraine and Europe as a whole, since such variants of the PSPP will be able to provide continuous power supply not only to enterprises of the mining complex, but also to the surrounding places – housing and communal services of cities and villages.

SECTION 2. EVALUATION OF EFFICIENCY OF PEAK PUMP-STORAGE POWER PLANTS WITHIN POWER SUPPLY SYSTEMS FOR IRON ORE UNDERGROUND MINES

2.1. Generalization of studies of efficiency of PSPPs as peak options for generating power supply at iron ore underground mines

At present, it is the current political situation that does dictate the need to approve options for a peak PSPP to ensure reliability and uninterrupted power supply as such strategic industries as mining, but also for residential areas adjacent to these enterprises. In this vision, the option of "peak" PSPPs is transformed into that of "backup" or "emergency".

However, both the first and second statements, before becoming an option of a real development, require its detailed evaluation.

Fig. 2.1 shows a generalizing structure of a PSPP’s development based on mine water drainage.

2.2. Modelling and preventive evaluation of power consumption by variability of structures for developing peak pump-storage power plants

LabVIEW enables creating a program (Fig. 2.2) for calculating power consumption of pumping units for conditions of specific parameters of operating iron ore underground mines during the day. This program is able to study and calculate basic parameters of a pumping unit at the preventive level, which can also operate in the generator mode. It enters data on the hourly pumping of a given volume of water in m^3/h. Also, the algorithm involves the use of tariff zones differentiated by time periods to pay for power consumed.

In mathematical simulation of pumping units of iron ore underground mines, the volume of water pumped to the surface was set at 370 m^3 (Fig. 2.3), which corresponds to real-life values of operating underground mines.

After modelling, the following results are obtained. During the day, the volume of mine waters of 8880 m^3/h was pumped out, while power consumed by two pumps makes 16729 kWh.

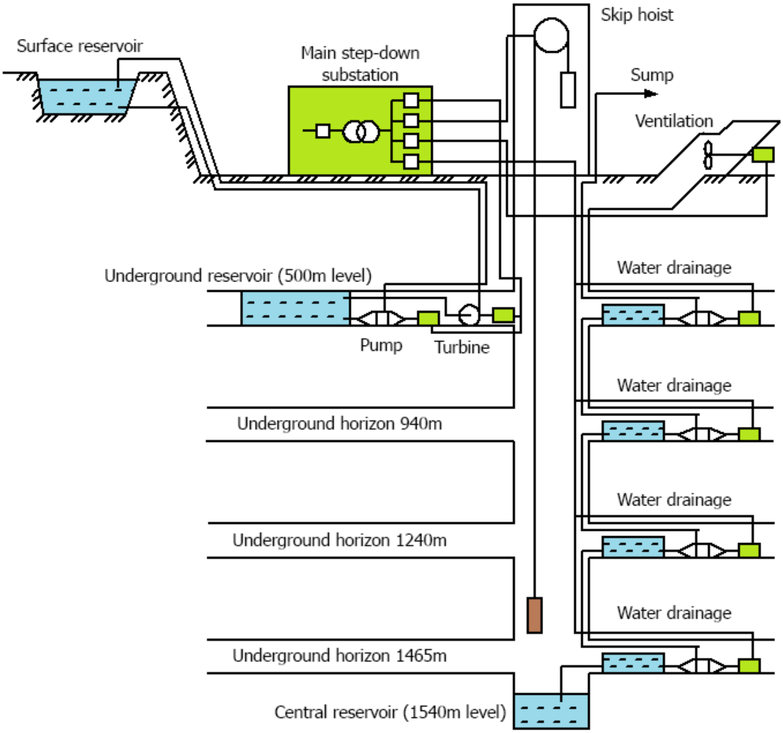

Figure 2.1 – Mine peak pump-storage power plant

Also, in the program, there is a section which calculates feasibility of using peak PSPPs in the structure of pumping units of iron ore underground mines. Fig. 2.4 indicates at what hours of the day the PSPP will operate, and we see that 6660 m^3/h of water is pumped out of the mine, 2220 m^3/h is pumped back to the mine, while 2183 kWh is generated during the day. This results in savings on pumping water per day, and power produced at a green tariff of 3 UAH/kWh per day.

Thus, mathematical simulation of the algorithm of the "smart" control system confirms the fact that there is a significant potential in creating peak PSPPs in iron ore mining.

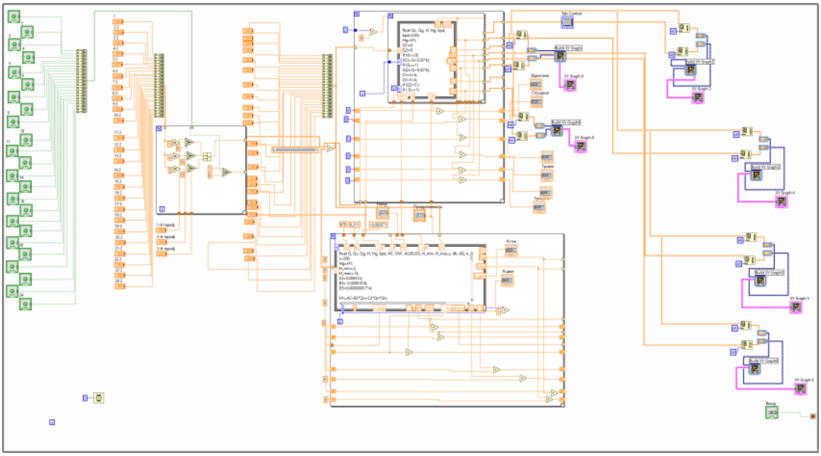

Figure 2.2 – Structure of the program of power consumption and generation by peak PSPPs at iron ore underground mines

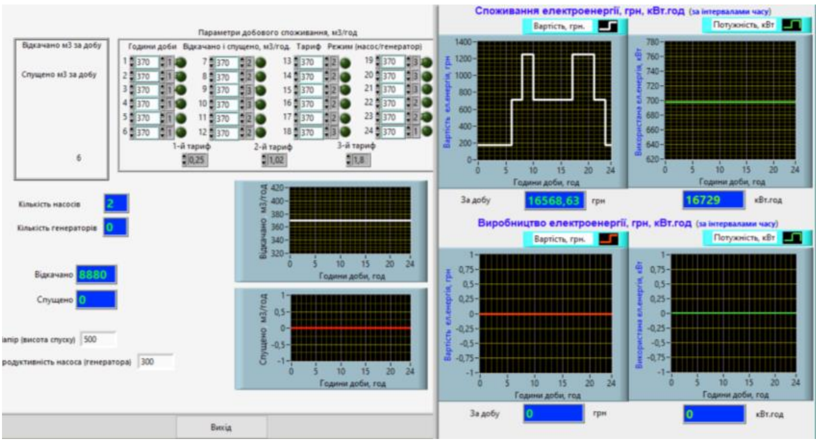

Figure 2.3 – Power consumption during the day at the iron ore underground mine

If we balance the systems by the value of the volume of pumping water, which should be 8500 m^3 per day, in this option it is necessary to raise the pumping volume to 615 m^3/h and redistribute generation periods of the peak PSPP during the day, namely for the period from 9am to 6pm.

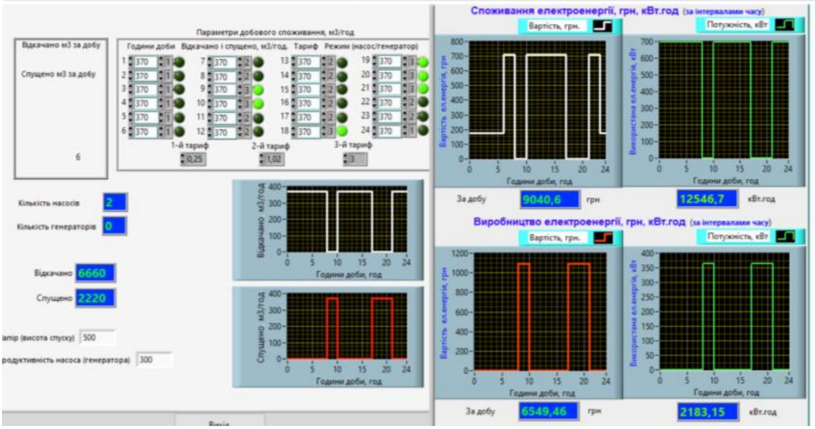

Figure 2.4 – Curves of power consumption and generation during the day at the iron ore underground mine

Modelling (Fig. 2.5) indicates that during the day we pump out 8610 m^3 of water from the underground mine, while 16220 kWh of power is consumed, and during generation in the specified period 3638 kWh of power is generated. At the same time, the daily water drainage is not reduced and 3638 kWh of power is generated using the peak PSPP.

At the next stage of the research, calculations are made for the option of installing peak PSPPs with two hydroturbines on the 500 m level of a typical iron ore underground mine. This possibility is provided by increasing the pump-storage potential due to additional volumes of water from neighboring underground mines. The costs of operation and repair, the net present value (NPV), the reduced tariff or the levelized cost of energy (LCOE) for power in systems with and without peak PSPPs (power supply only from the external network) are determined.

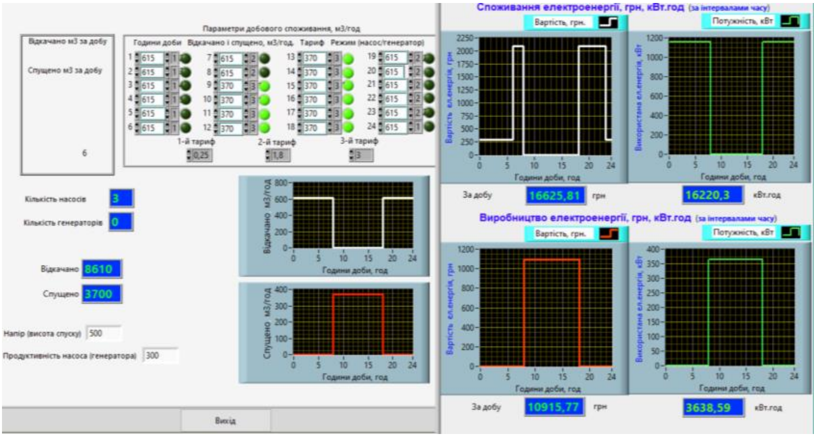

Figure 2.5 – Power consumption and generation of a balanced system at the iron ore underground mine

The costs of operation and repair, the NPV, the LCOE for power in systems with and without peak PSPP (power supply only from the external network) are determined.

The best system is the one in which the NPV is lower in the modular value.

2.3. Developing PSPP structures on the platform of main water drainage facilities at iron ore underground mines

According to the structural technology of developing water drainage facilities, iron ore underground mines are divided into objects with an individual water drainage system, when a mine independently pumps out the entire volume of water flow to the surface, and into group ones, when groundwater from several mines accumulates in the tank of one mine and from there is pumped into the surface tank.

In the latter type, water from water drainage satellites of the main underground mine can enter the main tanks both independently and by intermediate pumps. At the same time, both in the first and in the second option of the drainage structure, the peak PSPP should be built at the main underground mine – where the basic storage tank is located.

Fig. 2.6 shows one option of the structure of the project for developing a peak PSPP based on the underground mine complex for water drainage of a typical iron ore underground mine [29, 75].

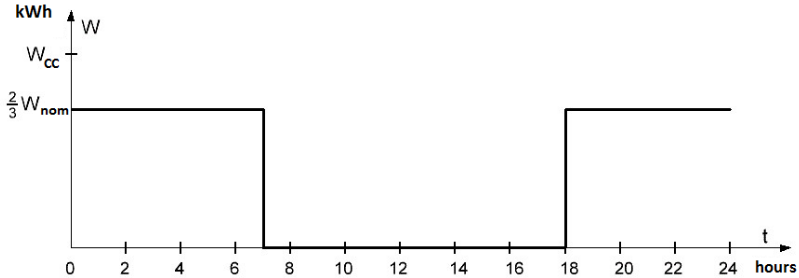

Figure 2.6 – Ideal curve of functioning of the synergistic water drainage facility and PSPPs: W_{cc} is volumes of centralized power consumption from the generating company; $2/3 \cdot W_{nom}$ is the maximum allowable level of power consumption according to the ordered volumes of the enterprise for the current day

According to the theoretical data in Sections 2 and 3, in the ideal case, the schedule of functioning of the synergistic power complex of the PSPP– water drainage for underground mines should be in the form shown in Fig. 2.6.

At the same time, the maximum level of power consumption according to the ordered volumes of the enterprise for the current day should correspond to the minimum permissible value determined by the functioning technology of the underground mine's power consumers.

As indicated in the previous sections of this research, in Ukraine and other countries there are both operating underground mines and decommissioned or abandoned ones. Pump-storage facilities can be installed in decommissioned underground mines, thus ensuring accumulation of mine water at night and generation of power during peak hours to cover the deficit or equalize electrical load curves. This is applicable to industrial cities, where, along with mining enterprises, there may be other powerful consumers who create a significant impact on the quality of power in case of the centralized power grid.

At operating underground mines, pump-storage facilities can be installed on underground levels. Both on-surface tanks of the underground mine and those on underground levels are located in close proximity to a ventilation shaft, where pressure pump columns are installed for pumping mine water within pump-storage facilities.

Fig. 2.7 presents the option of the mine peak PSPP with a common pressure column.

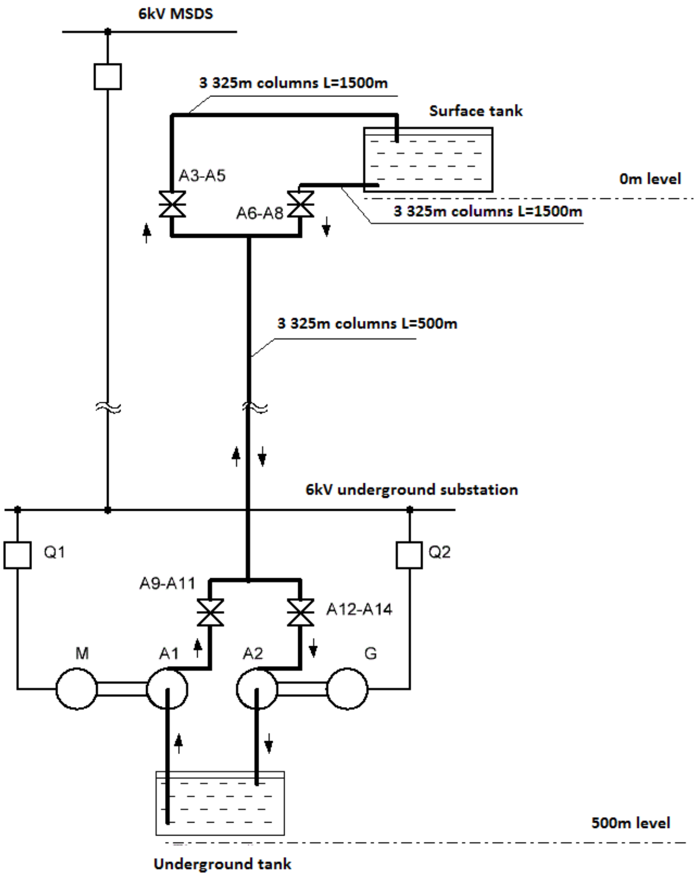

Fig. 2.7 – Peak PSPP with a common pressure pump column at the iron ore underground mine

The surface tank can be either open or closed. The tank capacity is determined by the required amount of power generated in the daytime:

$$V = \frac{W}{\gamma \cdot g \cdot H \cdot \eta}, m^3 , \quad (2.1)$$

where W is power, kWh;

γ is density of liquid used for pumping in the pump-storage system, kg/m^3;

g is acceleration of gravity, g = 9.81 m/s^2;

H is a difference in liquid levels of tanks, m;

η is the efficiency of the generator and the hydroturbine.

The volume of power generated is also affected by the water flow rate of pumps operating at night, the duration of the night period with a reduced power tariff and the capacity of pressure columns located in the shaft of the underground mine.

The presented diagram shows technical solutions for applying a pump-storage facility on the 500 m level with three pressure columns of a 325 mm diameter each. Switching of the surface pipes from the upper to the lower level and vice versa changing the direction of the water flow, as well as at the underground level from the pumps to the Pelton hydroturbine and vice versa is carried out using wedge valves with an electric drive. These valves can be controlled by a programmable logic controller, taking into account the night period. The Pelton hydroturbine drives a synchronous generator *G* with an output voltage of 6000V, which provides electric power to centrifugal CNS pumps with asynchronous motors *M*.

The power generated by the generator *G* is supplied to the 6 kV main step-down substation (MSDS) and covers the costs of internal consumers considering the total power balance when paying monthly for power to the power supplying company.

The option can be considered with two sets of pressure columns and a mine shaft: the first set of three pipes for pumping from the underground level to the surface and the second set of three pipes for discharging liquid from the surface to the underground level. In this case, the valves with an electric drive and a programmable logic controller are excluded.

Fig. 2.8 shows the mine peak PSPP without valves on the pressure columns. In this technological scheme, the length of the pipes of pressure columns increases, but the valves are excluded, this causing an increase in reliability of the peak PSPP.

To synchronize the output frequency of the synchronous generator, it is necessary to adjust its rotational speed by appropriate supply of mine water to the blades of the hydroturbine, or connect the synchronous generator to the supply network through a rectifier and a voltage inverter with pulse width modulation. Such an inverter provides power to the network with the required voltage and frequency.

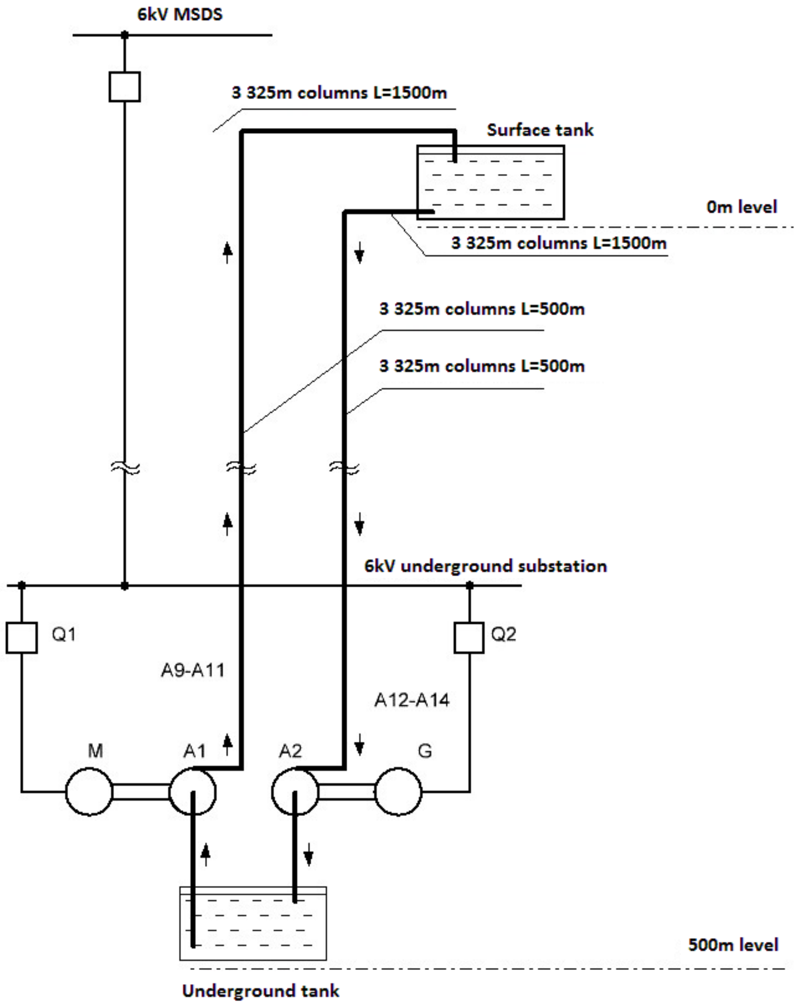

Figure 2.8 – Peak PSPP with separate pressure pump columns of an iron ore underground mine

2.4. Assessment of efficiency of distributed power generation systems with pumped-storage power plants for water drainage at iron ore mining enterprises

To make the above theoretical conclusions close to real-life conditions let us consider efficiency of introduction of mini-PSPPs for combined power supply of mine consumers taking water drainage of Rodina underground mine as an example. Main drainage facilities including pumps and reservoirs are located on the 500m, 940m, 1240m and 1315m levels. When conducting computational experiments, installation of 1 MW hydrogenerators of CJ A237-W-90/1x5.5 type is envisaged (Table 2.1).

Table 2.1 – Nominal parameters of the hydroturbine CJA 237

h, m	Q, m^3/sec	P, kW	n, rpm	Generator	Pн, 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 permissible water consumption [140]:

$$P = \eta \rho g h Q. \tag{2.2}$$

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 940 m levels. Power generation for 940 m-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-PSPPs are considered:

1. A single hydroturbine on the 500m level using water from one mine;
2. Two hydroturbines on the 500m level using water from several mines;
3. Four hydraulic turbines – 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:

1. From the industrial power grid supplied by the external power system.
2. Combined power supply of the grid and the mini-PSPP.

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-PSPP 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 [141]:

$$NPV = \sum_{i=1}^{N} \frac{R_i}{\left(1+d\right)^i}, \tag{2.3}$$

where R_i is the difference between profits and expenses for system operation, UAH;

d is the discount rate;

N is the number of years of system operation

Given that only the power system of the enterprise is considered separately and the sale of power generated by distributed generation facilities to external consumers is not envisaged, calculated indicators are used to determine the NPV value, namely cost of power purchased from the electricity company, capital costs for purchasing and installing generation equipment, annual operating costs and those for scheduled and preventive repairs. Since there is no revenue component, the NPV always takes a negative value. The preferred option is the system with the lowest NPV. For convenience, the modular cost value is used.

The economic index is used for modelling to take into account the cost of purchasing and maintaining power generation equipment of mini-PSPPs.

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.

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-PSPP 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-PSPPs 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/s; 0.15 m^3/s, and 0.07 m^3/s. 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%.

The computational experiment results are given in Tables 2.2 – 2.5.

Table 2.2 – Calculated NPV of the power supply system for the 500m level of Rodina mine with power costs of $\alpha_{ee} = 93{,}38\,UAH/MWh$

#	*E*, kWh/day	Hydrogenerator water consumption in, m^3/sec	NPV, UAH	
			Power supply from the grid	Power supply from the grid and the mini PSPP
1	10800	0.07	3929427.39	4744160.92
2	10800	0.15	3929427.39	2095383.12
3	10800	0.23	3929427.39	1820973.14
4	21600	0.07	7858854.77	8673588.3
5	21600	0.15	7858854.77	6024810.51
6	21600	0.23	7858854.77	2727270.31
7	43200	0.07	15717709.55	16532443.08
8	43200	0.15	15717709.55	13883665.28
9	43200	0.23	15717709.55	10586125.09

In Fig. 2.9-2.10, 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-PSPP containing a single hydroturbine with the tariff of $\alpha_{ee} = 93{,}38\,UAH/MWh$. The graphs specify economic indices for the enterprise grid and mini-PSPPs as well as total indices of the distributed generation system.

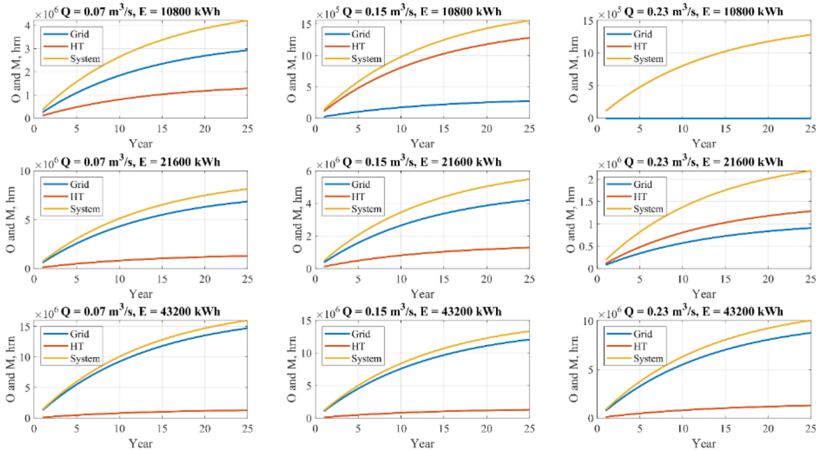

Figure 2.9 – Operating costs of the power supply system with the mini-PSPP for different values of hydroturbine water consumption and average daily power consumption with the power cost of $\alpha_{ee} = 93{,}38\, UAH/MWh$

The graphs indicate that at low power consumption and hydroturbine water consumption close to the nominal value with *Q=0.23m³/sec* and *E=10800kWh*, the NPV of the system is determined by operating costs of the mini-PSPP. 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 operator is not carried out. The distributed generation power system operates autonomously.

Under typical operation conditions with $Q=0.23\ m^3/sec$ and *E=21600 kWh* as well as $Q=0.15\ m^3/sec$ and *E=10800 kWh*, the NPV of the system is actually conditioned by the NPV of the mini-PSPP. Thus, the fraction of the NPV resulted from power generation via hydroturbines makes 86.9% with $Q=0.15\ m^3/sec$ and *E=10800 kWh* and 66.76% with $Q=0.23\ m^3/sec$ and *E=21600 kWh.*

With an increase in power consumption, the capacity shortage of the mini-PSPP begins to be covered by external power supply. With $Q=0.07\ m^3/sec$ and *E=21600 kWh;* $Q=0.07\ m^3/sec$ and *E=43200 kWh*; $Q=0.15\ m^3/sec$ and *E=43200 kWh;* $Q=0.23\ m^3/sec$ and *E=43200 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-PSPP.

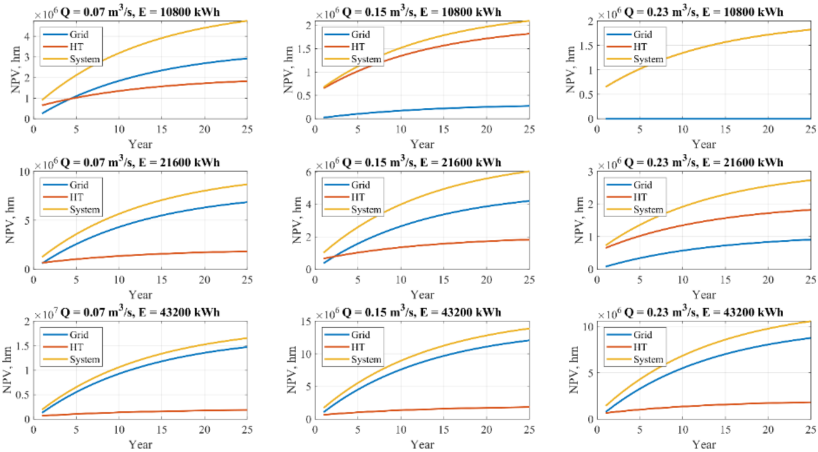

Figure 2.10 – NPV of the power supply system with the mini-PSPP for different values of hydroturbine water consumption and average daily power consumption with the power cost of $\alpha_{ee} = 93{,}38\, UAH/MWh$

Thus, the fraction of the NPV from hydroturbine operation in the total structure of the NPV system is only 11.01% with $Q=0.07\ m^3/sec$ and $E=43200\ kWh$, 13.12% with $Q=0.15\ m^3/sec$ and $E=43200\ kWh$, 20.99% with $Q=0.07\ m^3/sec$ and $E=21600\ kWh$, and 17.2% with $Q=0.07\ m^3/sec$ and $E=43200\ kWh$ 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-PSPP (Table 2.2) – it is established that with the increased Q to the nominal value of the hydrogenerator (0.23 m^3/sec), the NPV for the mini-PSPP system decreases. Thus, during the operation of power equipment with $E=21600\ kWh/day$ and $Q=0.15\ m^3/sec$, the NPV of the mini-PSPP system is 23.34% smaller as compared to the system without the mini-PSPP, and with $Q=0.23\ m^3/sec$ it is 65.3% smaller (41.96% greater than with $Q=0.15\ m^3/sec$).

In case of introducing two pumps, i.e. with increased power consumption up to $E=43200\ kWh/day$ with $Q=0.15\ m^3/sec$ for the mini-PSPP system, the NPV is 11.67% smaller and with $Q=0.23\ m^3/sec$ – 32.65% smaller (20.98% greater as compared to $Q=0.15\ m^3/sec$). So, with increased capacity of water drainage consumers, efficiency of the mini-PSPP 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 2.3 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-PSPP hydroturbine during mine water discharge, in particular with $Q=0.07\ m^3/sec$ 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 power generation leading to a great difference between the volume of power produced and consumed.

Additionally, a dependence of the NPV of the combined power supply system on hydroturbine water consumption and power consumption is built. There are also determined application areas of parameters within which it is advisable to use a particular pattern. Graphical interpretation of optimal applications of a certain power supply option is similar to *the Optimal System Plot* of *the Homer Pro* application package [142]. To perform calculations, intervals of changing independent parameters (hydroturbine water consumption and power consumption) are reduced. Thus, Q changes within [0.07 m^3/sec; 0.23 m^3/sec] in increments of $1 \cdot 10^4$ m^3/sec; average daily capacity – within [450 kW, 180 kW] in increments of 10 kW.

Table 2.3 – Power costs when introducing the distributed generation system with the mini-PSPP at the 500m level with the tariff of $\alpha_{ee} = 93.38\,UAH/MWh$

#	E, kWh/day	Hydrogenerator water consumption, m^3/sec	Power costs, UAH/kWh	
			Power supply from the grid	Power supply from the grid and the mini-PSPP
1	10800	0.07	0.09338	0.112742
2	10800	0.15	0.09338	0.049795
3	10800	0.23	0.09338	0.043274
4	21600	0.07	0.09338	0.103061
5	21600	0.15	0.09338	0.071588
6	21600	0.23	0.09338	0.032406
7	43200	0.07	0.09338	0.098220
8	43200	0.15	0.09338	0.082484
9	43200	0.23	0.09338	0.062893

In Fig. 2.12 and further in yellow, the area of the power supply system efficiency is indicated, which provides for power supply from the grid without mini-PSPPs, in blue – distributed generation systems with mini-PSPPs.

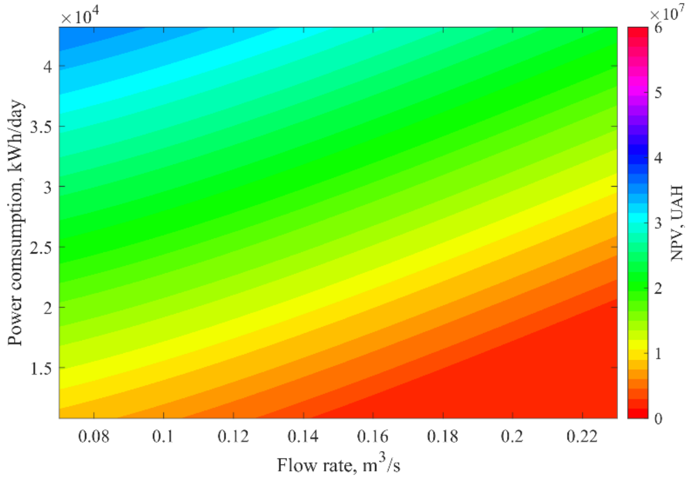

Figure 2.11 – Dependence of the NPV of the combined power supply system on hydroturbine water consumption and the level of power consumption with a single hydroturbine introduced on the 500m level with the tariff $\alpha_{ee} = 93{,}38\,UAH/MWh$

Analysis of the obtained results (Fig. 2.11, Fig. 2.12) shows that with the current power tariff $\alpha_{ee} = 93{,}38\,UAH/MWh$, the combined power supply system with a hydrogenerator should be used for water flow intensity above 0.1339 m^3/sec and average daily power consumption of 10800 kWh/day; 0.1899 m^3/sec – with 21600 kWh/day and 0.23 m^3/sec – with 29520 kWh/day. Reduced water consumption leads to the increased NPV for systems without mini-PSPPs as compared to the option without them, which indicates inefficiency of the combined power supply system. Power consumption over 29520 kWh makes application of the mini-PSPP system inefficient.

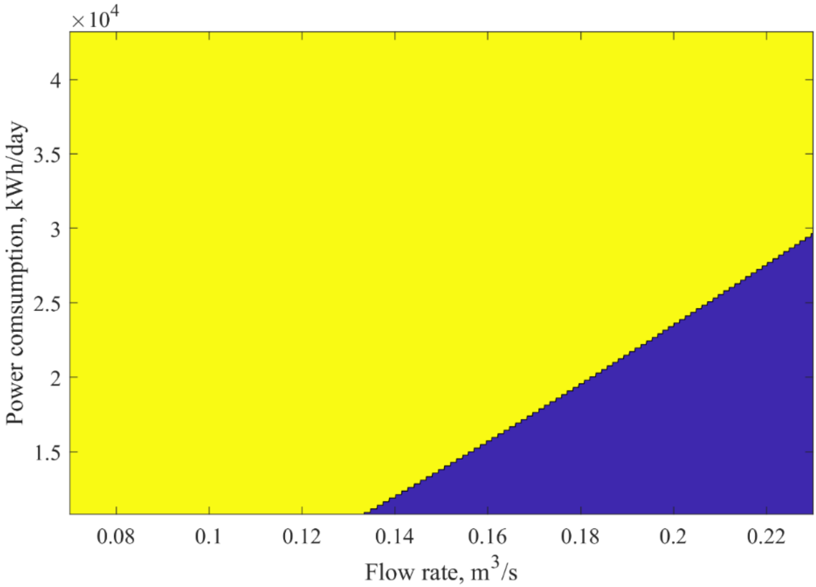

Figure 2.12 – Power supply system of the 500m level with a single turbine introduced which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff $\alpha_{ee} = 93.38\,UAH/MWh$

The area of effective application of the combined power supply system with its own distributed generation facilities within the considered change of parameters ($\alpha_{ee} = 93.38\,UAH/MWh$) 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.

Application of the tariff for peak hours ($\alpha_{ee} = 140.07\,UAH/MWh$ – Table 2.4, Fig. 2.13, Fig. 2.14) is expected to increase efficiency of the combined power supply system, with the single hydroturbine-based mini-PSPP on the 500 m level.

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.

Table 2.4 – Calculated NPV of power supply systems of the 500m level of Rodina mine with the power cost of $\alpha_{ee} = 140.07\,UAH/MWh$

#	*E*, kWh/day	Hydrogenerator water consumption, m^3/sec	NPV, UAH	
			Power consumption from the grid	Power consumption from the grid and the mini-PSPP
1	10800	0.07	5894141.08	6205754.8
2	10800	0.15	5894141.08	2232588.11
3	10800	0.23	5894141.08	1820973.14
4	21600	0.07	11788282.16	12099895.89
5	21600	0.15	11788282.16	8126729.19
6	21600	0.23	11788282.16	3180418.9
7	43200	0.07	23576564.32	23888178.05
8	43200	0.15	23576564.32	19915011.36
9	43200	0.23	23576564.32	14968701.06

Thus, in the most unfavourable operating conditions, the fraction of the NPV of mini-PSPPs for the peak tariff in the total structure of the system NPV decreases as compared to the basic tariff ($\alpha_{ee} = 93,38\,UAH/MWh$). For example, it makes 7.62% with $Q=0.07\ m^3/sec$ and $E=43200\ kWh$; 9.14% with $Q=0.15\ m^3/sec$ and $E=43200\ kWh$; 12.17% with $Q=0.23\ m^3/sec$ and $E=43200\ kWh$; 15.05% with $Q=0.07\ m^3/sec$ and $E=21600\ kWh$. 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-PSPPs decreases greatly for such conditions as $Q=0.07\ m^3/sec$, $E=10800\ kWh$ and $Q=0.15\ m^3/sec$, $E=21600\ kWh$ and amounts to 29.34% and 22.41% (38.38% and 30.22% with $\alpha_{ee} = 93,38\,UAH/MWh$) respectively. This is due to increased costs for power purchased from the external grid.

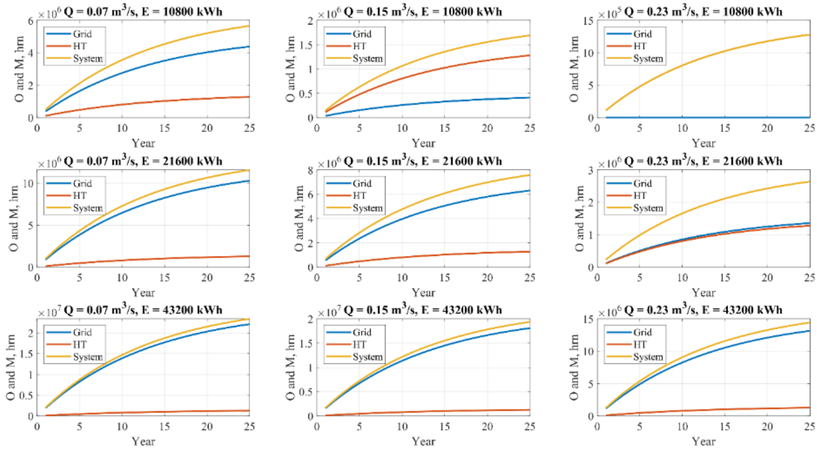

Figure 2.13 – Operating costs of the power supply system with mini-PSPPs during the operation period for different values of hydroturbine water consumption and average daily power consumption with the power cost $\alpha_{ee} = 140.07\, UAH/MWh$

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

The NPV of mini-PSPP systems increases more significantly with increased water consumption up to the nominal value as compared to the basic tariff. For example, with *E=21600 kWh*/day corresponding to the consumer's capacity of 900 kW, the NPV with *Q=0.15* m^3*/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* m^3*/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 kWh*/day, the NPV of the mini-PSPP system is 15.53% lower with *Q=0.15* m^3*/sec* (11.67% for the basic tariff) and 36.51% lower with *Q=0.23* m^3*/sec* (32.65 % for the basic tariff).

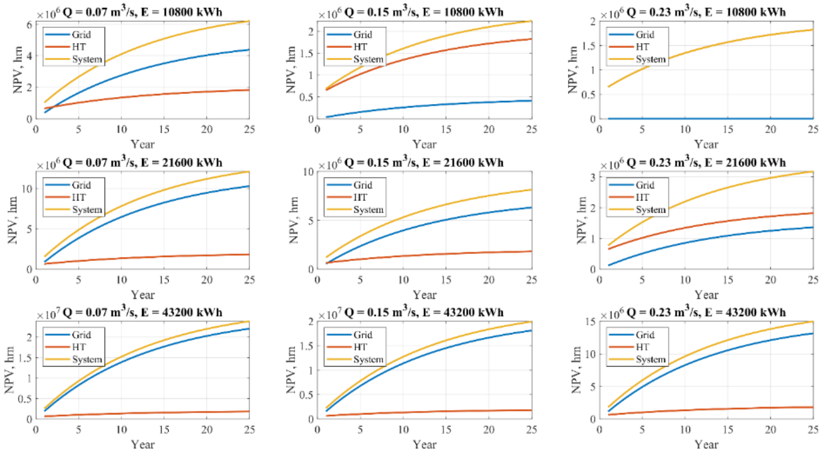

Figure 2.14 – NPV of the power supply system with mini-PSPPs during the operation period for different values of hydroturbine water consumption and average daily power consumption with the power cost
$\alpha_{ee} = 140.07\, UAH/MWh$

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-PSPPs is almost comparable – 73.02% vs. 65.3% for *E=21600 kWh*/day and 36.51% vs. 32.65% for *E=43200 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-PSPP system (Table 2.5) exceeds the peak tariff with $Q=0.07\ m^3/sec$ 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 $Q=0.15\ m^3/sec$ and *E=43200 kWh*/day and lower by only 15.53%.

Table 2.5 – Power costs with the mini-PSPP distributed generation system introduced on the 500m level with the tariff of $\alpha_{ee} = 140.07\, UAH/MWh$

#	*E*, kWh/day	Hydrogenerator water consumption, m^3/sec	Power cost, UAH/kWh	
			Power consumption from the grid	Power consumption from the grid and the mini-PSPP
1	10800	0.07	0.14007	0.147475
2	10800	0.15	0.14007	0.053056
3	10800	0.23	0.14007	0.043274
4	21600	0.07	0.14007	0.143773
5	21600	0.15	0.14007	0.096563
6	21600	0.23	0.14007	0.037790
7	43200	0.07	0.14007	0.141921
8	43200	0.15	0.14007	0.118316
9	43200	0.23	0.14007	0.088930

In Fig. 2.15, the dependence graph $NPV = f(Q, E)$ shows a more intensive increase in the NPV with increased power consumption and reduced hydroturbine water consumption.

The graph (Fig. 2.16) reveals that the system without mini-PSPPs should be used with water flow intensity below 0.1264 m^3/sec for *E=10800 kWh*/day, 0.1839 m^3/sec – for *E=21600 kWh*/day and 0.23 m^3/sec – for *E=30960 kWh*/day. That is, the application area of the distributed generation system with mini-PSPPs increases to 19.6% compared to the tariff of $\alpha_{ee} = 93{,}38\, UAH/MWh$, yet not significantly – only by 2.4%. With the level of power consumption above *30960 kWh*/day, the use of the mini-PSPP system is inefficient.

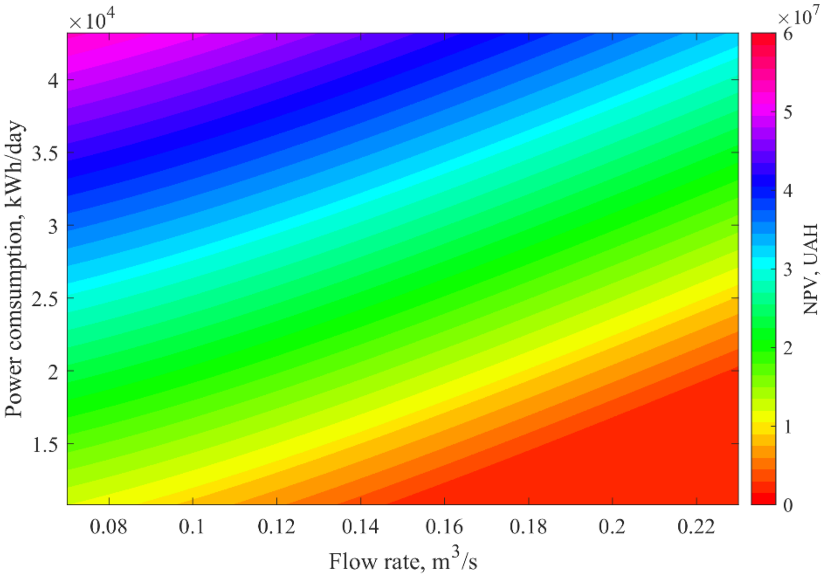

Figure 2.15 – Dependence of the NPV of the combined power supply system on hydroturbine water consumption and power consumption $NPV = f(Q,E)$ with a single hydroturbine introduced on the 500m level with the tariff $\alpha_{ee} = 140.07\,UAH/MWh$

At the next stage of the research, calculations are made for the option with two hydroturbines installed on the 500m level of Rodina mine by increasing the storage pump potential through additional water supplied from several adjacent underground mines. Similar to the previous case, operating and repair costs, the NPV, the reduced power in the systems with and without mini-PSPPs are determined with the corresponding dependence graphs built. Cases of purchasing power from the external distribution operator at basic ($\alpha_{ee} = 93{,}38\,UAH/MWh$) and peak tariffs ($\alpha_{ee} = 140.07\,UAH/MWh$) are considered. There are determined areas of changed water consumption via storage pumps and the power consumption level at which it is advisable to implement one or another option of power supply to consumers.

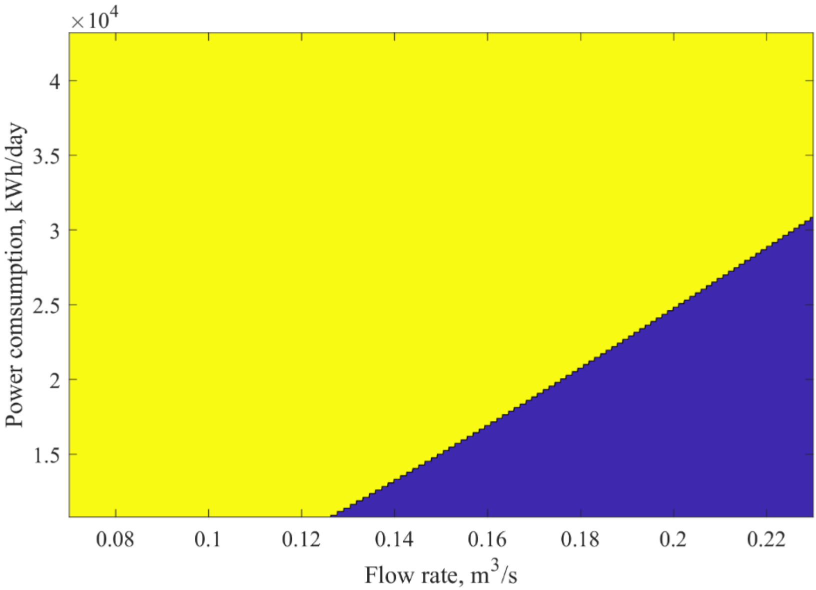

Figure 2.16 – Power supply system of the 500m level with a single turbine introduced, which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff $\alpha_{ee} = 140.07\,UAH/MWh$

Computational experiment results for the basic tariff of $\alpha_{ee} = 93{,}38\,UAH/MWh$ are summarized in Tables 2.6 and 2.7 followed by their graphical representation in Fig. 2.17 – 2.20.

The data obtained reveals an increase in the fraction of the NPV of mini-PSPPs in the structure of the system NPV (Fig. 2.17 and Fig. 2.18). 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.

Thus, according to Fig. 2.18, for previously identified three most unfavourable conditions of mini-PSPP application with $Q=0.07\ m^3/sec$ and $E=21600\ kWh$/day, $Q=0.07\ m^3/sec$ and $E=43200\ kWh$/day and with $Q=0.15\ m^3/sec$ and $E=43200\ kWh$/day, the fraction of the NPV makes 29.34%, 15.04% and 22.41% respectively. In other words, the fraction increases significantly compared to the option with one storage pump used, but still does not exceed the discounted cost of purchasing power from the external power grid for 25 years.

Table 2.6 – Calculated NPV of power supply systems for Rodina mine consumers with power costs $\alpha_{ee} = 93,38\, UAH/MWh$

#	*E*, kWh/day	Hydrogenerator water consumption, m^3/sec	NPV, UAH	
			Power consumption from the grid	Power consumption from the grid and mini-PSPPs (two hydroturbines)
1	10800	0.07	3929427.39	5558894.45
2	10800	0.15	3929427.39	3641946.29
3	10800	0.23	3929427.39	3641946.29
4	21600	0.07	7858854.77	9488321.83
5	21600	0.15	7858854.77	4190766.25
6	21600	0.23	7858854.77	3641946.29
7	43200	0.07	15717709.55	17347176.61
8	43200	0.15	15717709.55	12049621.02
9	43200	0.23	15717709.55	5454540.63

With $Q=0.07\ m^3/sec$ and $E=10800\ kWh$/day, with $Q=0.15\ m^3/sec$ and $E=21600\ kWh$/day and with $Q=0.23\ m^3/sec$ and $E=43200\ kWh$/day, the NPV of the system begins to depend mainly on the NPV of the mini-PSPP (55.88%, 81.56% and 57.26% respectively). However, with $Q=0.15\ m^3/sec$ and $E=10800\ kWh$/day, $Q=0.23\ m^3/sec$ and $E=10800\ kWh$/day and with $Q=0.23\ m^3/sec$ and $E=21600\ kWh$/day, the NPV of the system is completely determined by hydroturbine consumption which is explained by increased generation to the level of autonomous power supply to consumers.

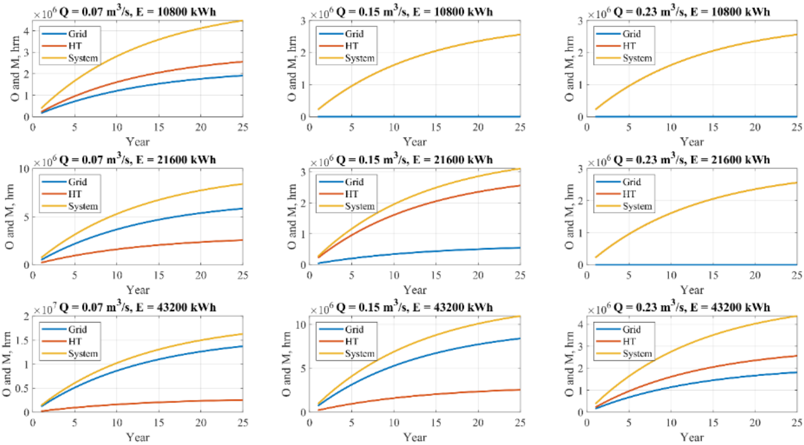

Figure 2.17 – Operating costs of the power supply system with the mini-PSPP (two hydroturbines on the 500m level) during the period of operation for different values of hydroturbine water consumption and average daily power consumption with power costs $\alpha_{ee} = 93.38\, UAH/MWh$

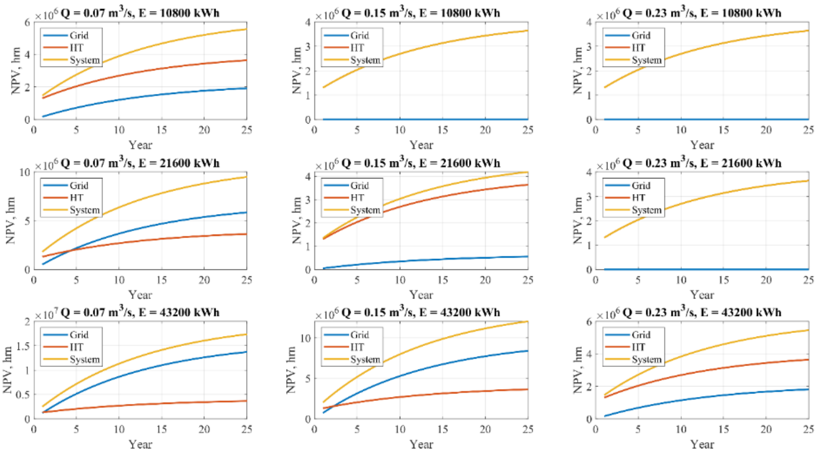

Figure 2.18 – NPV of the power supply system with the mini-PSPP (two hydroturbines on the 500m level) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs $\alpha_{ee} = 93.38\, UAH/MWh$

However, comparing the results are in Table 2.3 and Table 2.7, it can be seen that the reduced power cost in the mini-PSPP system with two hydroturbines is growing. This is due to double capital expenses for purchasing generation equipment and annual expenses for maintenance and repairs.

As in the above cases, with water consumption via storage pumps which increases to the nominal value, the NPV of the combined power supply system with the mini-PSPP is smaller than the NPV of the system supplied only by the grid. With power consumption *E=43200 kWh*/day, it is 57.94% lower, with *E=21600 kWh*/day – 64.52% lower and with *E=10800 kWh*/day – 29.05% lower.

The power cost (Table 2.7) exceeds the tariff set by the power supplying company for all power consumption options with $Q=0.07\ m^3/sec$. With $Q=0.15\ m^3/sec$, $Q=0.23\ m^3/sec$ and *E=10800 kWh*/day, the NPV is close to the basic tariff and only 7.32% smaller.

Table 2.7 – Power costs for the distributed generation system with two hydroturbines introduced on the 500 m level with the tariff $\alpha_{ee} = 93.38\,UAH/MWh$

#	*E*, kWh/day	Hydrogenerator water consumption, m³/sec	Power costs, UAH/kWh	
			Power consumption from the grid	Power consumption from the grid and mini-PSPPs (two hydroturbines)
1	10800	0.07	0.09338	0.132103
2	10800	0.15	0.09338	0.086548
3	10800	0.23	0.09338	0.086548
4	21600	0.07	0.09338	0.112742
5	21600	0.15	0.09338	0.049795
6	21600	0.23	0.09338	0.043274
7	43200	0.07	0.09338	0.103061
8	43200	0.15	0.09338	0.071588
9	43200	0.23	0.09338	0.032406

When comparing graphs in Fig. 2.11 and Fig. 2.19, it can be stated that the growth rate of the system NPV decreases due to the higher initial value of the NPV in the area which corresponds to higher hydroturbine water consumption and lower power consumption.

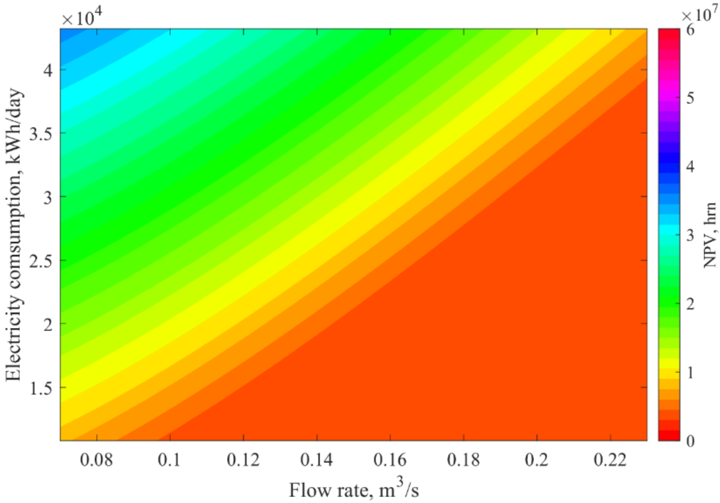

Fig. 2.19. Dependence $NPV = f\left(Q, E\right)$ for two hydroturbines introduced on the 500m level ($\alpha_{ee} = 93.38\, UAH/MWh$)

The graph (Fig. 2.20) shows that the system without the mini-PSPP should be applied to water flow intensity below 0.1006 m^3/sec with *E=10800 kWh*/day, 0.1334 m^3/sec – with *E=21600 kWh*/day and 0.1906 m^3/sec – with *E=43200 kWh*/day. That is, the area of applying the distributed generation system with the mini-PSPP and two hydroturbines increases significantly and makes 51.57%, which is 37.37% and 31.97% greater than for the system with a single storage pump facility with the basic and peak tariffs respectively.

When applying the peak power tariff to hydroturbines operating with nominal water consumption of 0.23 m^3/sec, the NPV of the mini-PSPP system is 38.21%, 69.12% and 73.02% smaller with power consumption *E=43200 kWh*/day, *E=21600 kWh*/day and *E=10800 kWh*/day respectively than to the system without the mini-PSPP, the results of calculations in Table 2.8 confirming this. Compared with the option with the basic tariff (Table 2.6), it can be seen that the NPV criterion indicates increased efficiency of distributed generation systems because the difference between NPVs becomes more significant.

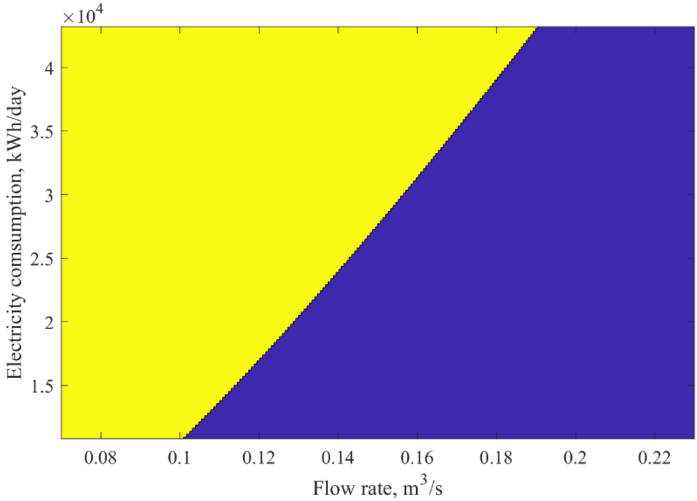

Figure 2.20 – Power supply system with two hydroturbines introduced on the 500m level which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff of $\alpha_{ee} = 93.38\,UAH/MWh$

With $Q=0.07$ m^3/sec and $E=10800$ *kWh*/day, $Q=0.15$ m^3/sec and $E=21600$ *kWh*/day and $Q=0.23$ m^3/sec and $E=43200$ *kWh*/day, the NPV of the system mainly depends on the NPV of the mini-PSPP, the fraction of which for these parameters is 55.88%, 81.56% and 57.25% respectively. That is, in the first and the last case, NPVs are almost equal to the discounted cost of purchased power from the external power grid. With $Q=0.15$ m^3/sec and $E=10800$ *kWh*/day, $Q=0.23$ m^3/sec and $E=10800$ *kWh*/day, $Q=0.23$ m^3/sec and $E=21600$ *kWh*/day, autonomous power supply is carried out from the facility's own sources of generation.

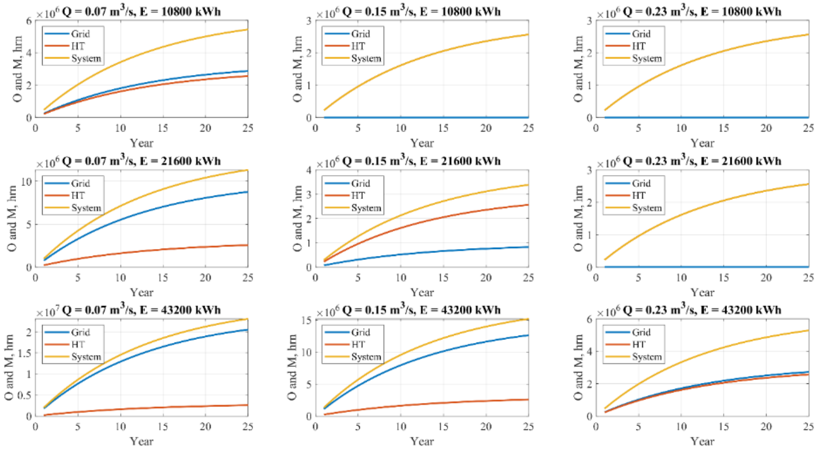

Figure 2.21 – Operating costs of the power supply system with the mini-PSPP (two hydroturbines on the 500m level) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs $\alpha_{ee} = 140.07\, UAH/MWh$

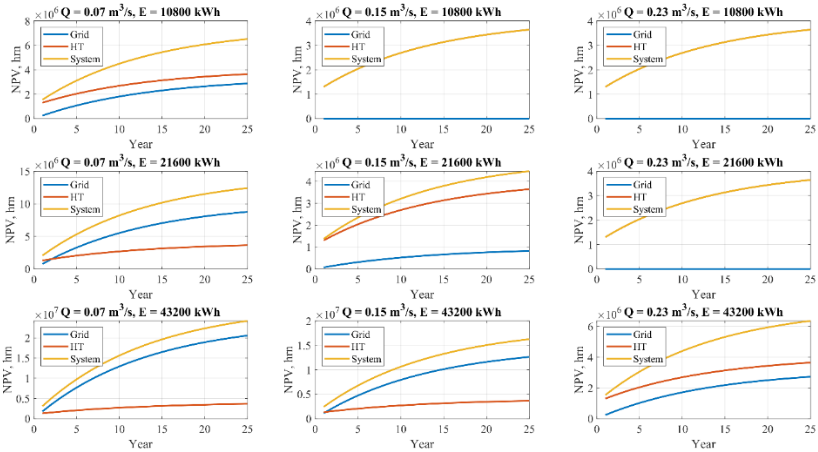

Figure 2.22 – NPV of the power supply system with the mini-PSPP (two hydroturbines on the 500m level) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs $\alpha_{ee} = 140.07\, UAH/MWh$

Table 2.8 – Calculated NPV of power supply systems for Rodina mine consumers with the power cost $\alpha_{ee} = 140.07\,UAH/MWh$

#	*E*, kWh/day	Hydrogenerator water consumption, m^3/sec	NPV, UAH	
			Power consumption from the grid	Power consumption from the grid and mini-PSPPs (two hydroturbines)
1	10800	0.07	5894141.08	6517368.53
2	10800	0.15	5894141.08	3641946.29
?	10800	0.23	5894141.08	3641946.29
4	21600	0.07	11788282.16	12411509.61
5	21600	0.15	11788282.16	4465176.23
6	21600	0.23	11788282.16	3641946.29
7	43200	0.07	23576564.32	24199791.77
8	43200	0.15	23576564.32	16253458.39
9	43200	0.23	23576564.32	6360837.8

Data on the calculated reduced power cost in the system with two storage pumps (Table 2.9) 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 2.7), its cost increases and, except for cases when *Q=0.07 m^3/sec*, it remains below $\alpha_{ee} = 140.07\,UAH/MWh$.

The graph (Fig. 2.24) reveals that the system without the mini-PSPP should be used at water flow intensity below 0.0926 m^3/sec with *E=10800 kWh*/day, 0.1261 m^3/sec – with *E=21600 kWh*/day and 0.1839 m^3/sec – with *E=43200 kWh*/day. It means that the application area of the power supply system with the mini-PSPP slightly expands by 4.34% to 55.91% compared to the option in Fig. 2.13 which corresponds to the basic tariff.

Table 2.9 – Power costs for the distributed generation system with two hydroturbines introduced on the 500m level with the tariff of $\alpha_{ee} = 140.07\,UAH/MWh$

#	*E*, kWh/day	Hydrogenerator water consumption, m^3/sec	Power costs, UAH/kWh	
			Power consumption from the grid	Power consumption from the grid and mini-PSPPs (two hydroturbines)
1	10800	0.07	0.14007	0.154881
2	10800	0.15	0.14007	0.086548

3	10800	0.23	0.14007	0.086548
4	21600	0.07	0.14007	0.147475
5	21600	0.15	0.14007	0.053056
6	21600	0.23	0.14007	0.043274
7	43200	0.07	0.14007	0.143773
8	43200	0.15	0.14007	0.096563
9	43200	0.23	0.14007	0.037790

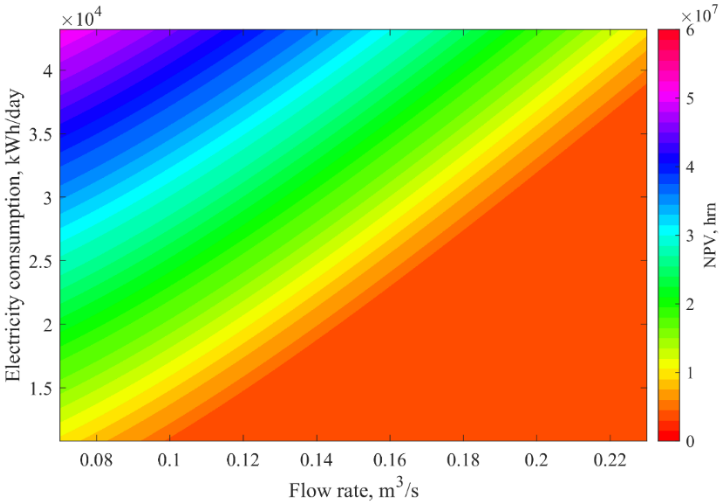

Figure 2.23 – Dependence $NPV = f(Q, E)$ for two hydroturbines introduced on the 500m level with the tariff $\alpha_{ee} = 140.07\, UAH/MWh$

Table 2.9 – Power costs for the distributed generation system with two hydroturbines introduced on the 500m level with the tariff of $\alpha_{ee} = 140.07\, UAH/MWh$

#	*E*, kWh/day	Hydrogenerator water consumption, m^3/sec	Power costs, UAH/kWh	
			Power consumption from the grid	Power consumption from the grid and mini-PSPPs (two hydroturbines)
1	10800	0.07	0.14007	0.154881
2	10800	0.15	0.14007	0.086548
3	10800	0.23	0.14007	0.086548

4	21600	0.07	0.14007	0.147475
5	21600	0.15	0.14007	0.053056
6	21600	0.23	0.14007	0.043274
7	43200	0.07	0.14007	0.143773
8	43200	0.15	0.14007	0.096563
9	43200	0.23	0.14007	0.037790

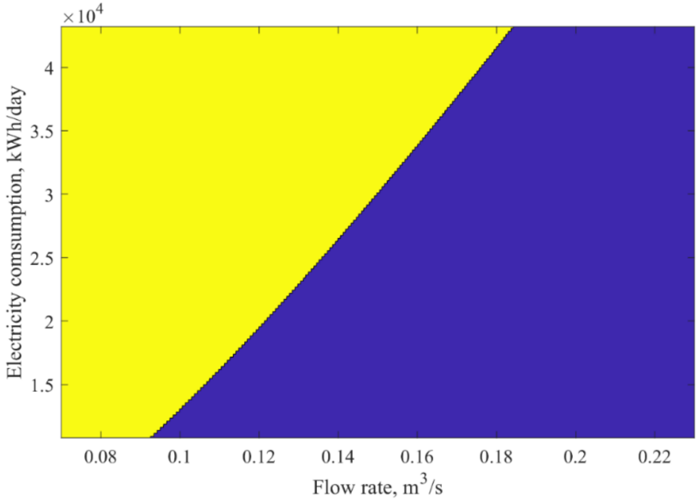

Figure 2.24 – Power system with two hydroturbines introduced on the 500m level which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff $\alpha_{ee} = 140.07\,UAH/MWh$

At the final stage, efficiency of introducing the distributed generation system with mini-PSPPs 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 2.10) indicates that the NPV of the mine power supply system with the mini-PSPP 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-PSPP 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.

Table 2.10 – Calculated NPV of power supply systems for consumers of Rodina mine with the power cost of $\alpha_{ee} = 93{,}38\, UAH/MWh$

#	*E*, kWh/day	Hydrogenerator water consumption, m^3/sec	NPV, UAH	
			Power consumption from the grid	Power consumption from the grid and mini-PSPPs (four hydroturbines)
1	10800	0.07	3929427.39	7283892.57
2	10800	0.15	3929427.39	7283892.57
3	10800	0.23	3929427.39	7283892.57
4	21600	0.07	7858854.77	11117788.9
5	21600	0.15	7858854.77	7283892.57
6	21600	0.23	7858854.77	7283892.57
7	43200	0.07	15717709.55	18976643.67
8	43200	0.15	15717709.55	8381532.49
9	43200	0.23	15717709.55	7283892.57

Analysis of the components of the NPV system with combined power supply (Fig. 2.25, Fig. 2.26) indicates a greater increase in the fraction of the NPV of mini-PSPPs 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 NPV of the mini-PSPP 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-PSPP are actually equal.

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%.

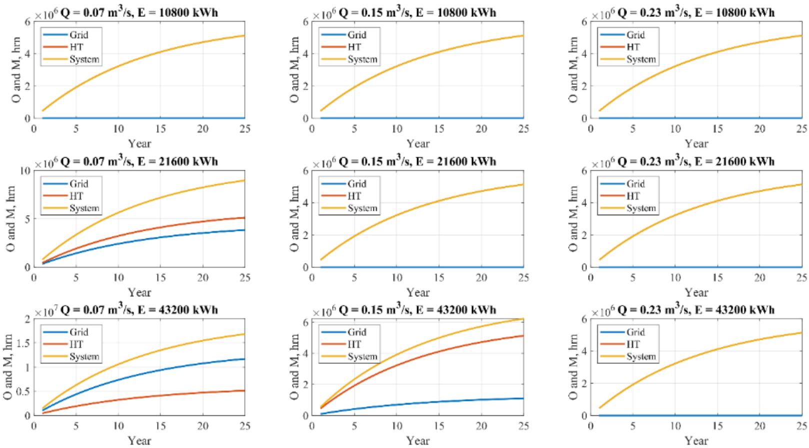

Figure 2.25 – Operating costs of the power supply system with the mini-PSPP (two and two hydroturbines on the 500m and 940m levels) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs of

$$\alpha_{ee} = 93{,}38\, UAH/MWh$$

A significant increase in the costs of generation equipment (four hydroturbines) and its further maintenance leads to exceeding the tariff $\alpha_{ee} = 93.38\, UAH/MWh$ by the reduced power cost in the distributed generation system except for *E=21600 kWh*/day and *E=43200 kWh*/day with water consumption *Q=0.15* m^3/sec and *Q=0.23* m^3/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-PSPP 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-PSPPs on the 500m and 940m levels more efficient, it is necessary to supply power to more consumers.

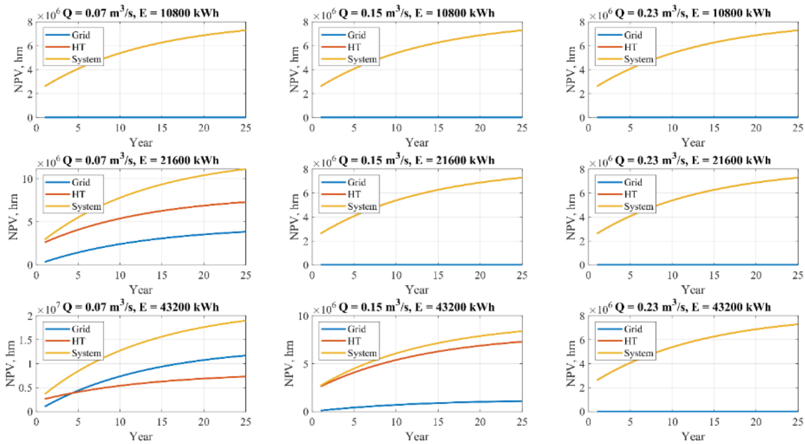

Figure 2.26 – NPV of the power supply system with the mini-PSPP (two and two hydroturbines on the 500m and 940m levels) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs $\alpha_{ee} = 93{,}38\,UAH/MWh$

Table 2.11 – Power costs for the distributed generation systems with mini-PSPPs introduced on the 500m and 940m levels with the tariff of $\alpha_{ee} = 93{,}38\,UAH/MWh$

#	*E*, kWh/day	Hydrogenerator water consumption, m^3/sec	Power costs, UAH/kWh	
			Power consumption from the grid	Power consumption from the grid and mini-PSPPs (four hydroturbines)
1	10800	0.07	0.09338	0.173096
2	10800	0.15	0.09338	0.173096
3	10800	0.23	0.09338	0.173096
4	21600	0.07	0.09338	0.132103
5	21600	0.15	0.09338	0.086548
6	21600	0.23	0.09338	0.086548
7	43200	0.07	0.09338	0.112742
8	43200	0.15	0.09338	0.049795
9	43200	0.23	0.09338	0.043274

The dependence graph $NPV = f(Q,E)$ in Fig. 2.27 shows an increase in the system NPV in the area of increasing power consumption from *E=10800 kWh*/day to *E=32100 kWh*/day and water consumption from *Q=0.12* m^3/sec to *Q=0.23* m^3/sec (indicated in orange).

The graph (Fig. 2.28) shows that the system without mini-PSPPs should be used for water flow intensity below 0.1011 m^3/sec with *E=21600 kWh*/day and 0.1336 m^3/sec – with *E=43200 kWh*/day. The peculiarity of this case is that with power consumption below *E=20160 kWh*/day mini-PSPPs 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.

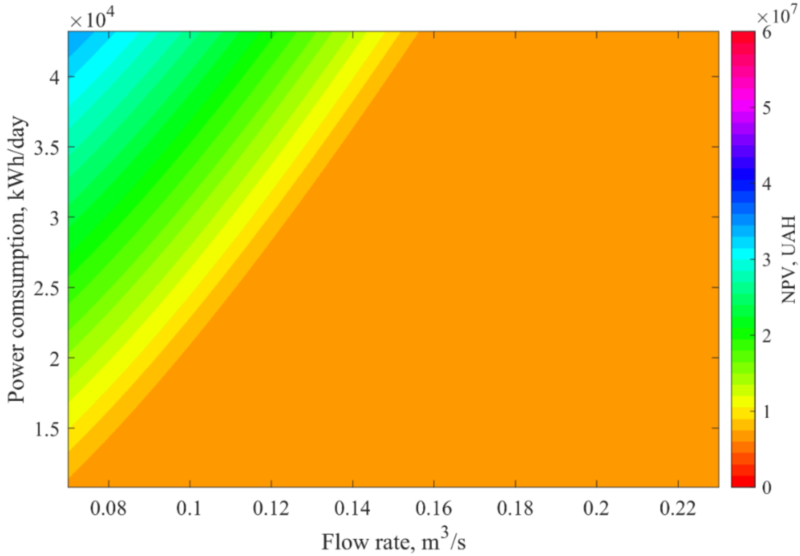

Figure 2.27 – Dependence of the NPV of the combined power supply system on hydroturbine water consumption and the level of power consumption $NPV = f(Q,E)$ with two hydroturbines introduced on the 500m level and two hydroturbines introduced on the 940m level with the tariff of $\alpha_{ee} = 93{,}38\, UAH/MWh$

With the peak tariff of $\alpha_{ee} = 140.07\, UAH/MWh$ in action, the NPV of the proposed power supply system with the mini-PSPP is lower than the NPV of the system in which consumers are supplied only from the external power grid with power consumption *E=21600 kWh*/day and *E=43200 kWh*/day and water consumption *Q=0.15* m^3/sec and *Q=0.23* m^3/sec (Table 2.12). Thus, with *Q=0.15* m^3/sec, *E=21600 kWh*/day and *Q=0.23* m^3/sec, *E=21600 kWh*/day, it reduces by 62.12 %, while with *Q=0.23* m^3/sec, *E=43200 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 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.

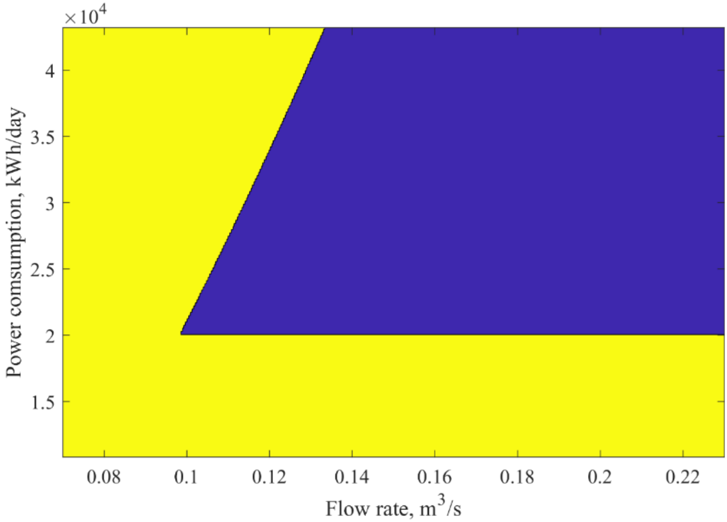

Figure 2.28 – Power supply system with four hydroturbines introduced on the 500m and 940m levels which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff of $\alpha_{ee} = 93{,}38\, UAH/MWh$

Analysis of the NPV components of the combined power supply system (Fig. 2.29 and Fig. 2.30) shows that with parameters *Q=0.07* m^3/sec, *E=43200 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 $\alpha_{ee} = 93{,}38\, UAH/MWh \cdot$

In such conditions as *Q=0.15 m³/sec* and *E=43200 kWh*/day, the fraction of the NPV of the mini-PSPP exceeds the NPV of the enterprise grid by 63.12% and is 81.56% vs. 18.44% respectively (Fig. 2.29, Fig. 2.30). With *Q=0.07 m³/sec* and *E=21600 kWh*/day, they take almost the same values – the NPV of the grid exceeds that of the mini-PSPP 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-PSPP as the generated power is sufficient for autonomous power supply of water drainage consumers.

Table 2.12 – Calculated NPV of power supply systems for consumers of Rodina mine with the power cost $\alpha_{ee} = 140.07\, UAH/MWh$

#	*E*, kWh/day	Hydrogenerator water consumption, m^3/sec	NPV, UAH	
			Power consumption from the grid	Power consumption from the grid and mini-PSPPs (four hydroturbines)
1	10800	0.07	5894141.08	7283892.57
2	10800	0.15	5894141.08	7283892.57
3	10800	0.23	5894141.08	7283892.57
4	21600	0.07	11788282.16	13034737.06
5	21600	0.15	11788282.16	7283892.57
6	21600	0.23	11788282.16	7283892.57
7	43200	0.07	23576564.32	24823019.22
8	43200	0.15	23576564.32	8930352.45
9	43200	0.23	23576564.32	7283892.57

Given that in this case the power tariff increases by a factor of 1.5 up to $\alpha_{ee} = 140.07\, UAH/MWh$ and, accordingly, the cost of its purchase from the distribution operator increases, the reduced power cost of the distributed generation system with the mini-PSPP (Table 2.13) becomes lower than the current tariff not only with *Q=0.23 m³/sec* as for $\alpha_{ee} = 93.38\, UAH/MWh$, but also with *Q=0.15 m³/sec*, i.e. the energy potential of water drainage is used more efficiently.

The dependence graph $NPV = f(Q,E)$ in Fig. 2.31 shows a more intensive increase in the NPV with increased power consumption and reduced hydroturbine water consumption.

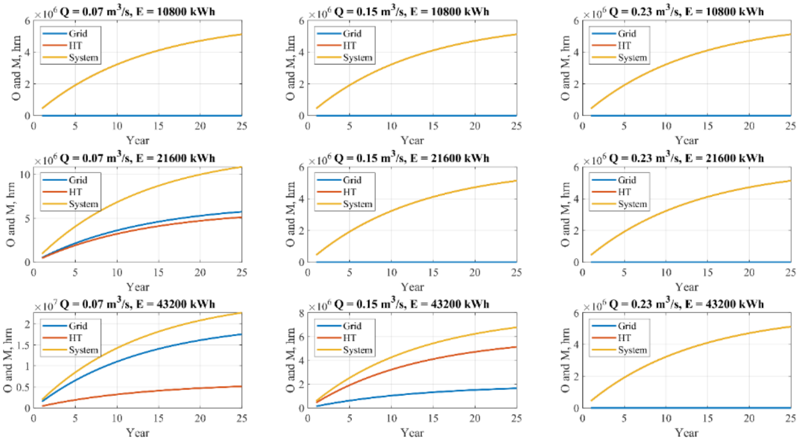

Figure 2.29 – Operating costs of the power supply system with the mini-PSPP (two and two hydroturbines on the 500m and 940m levels) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs

$$\alpha_{ee} = 140.07\, UAH/MWh$$

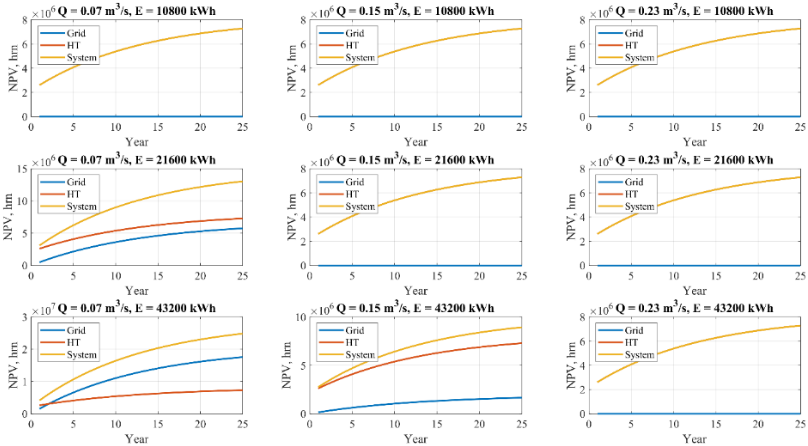

Figure 2.30 – NPV of the power supply system with the mini-PSPP (two and two hydroturbines on the 500m and 940m levels) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs of

$$\alpha_{ee} = 140.07\, UAH/MWh$$

Table 2.13 – Power costs for the distributed generation systems with mini-PSPPs introduced on the 500m and 940m levels with the tariff of $\alpha_{ee} = 140.07\, UAH/MWh$

#	*E*, kWh/day	Hydrogenerator water consumption, m^3/sec	Power costs, UAH/kWh	
			Power consumption from the grid	Power consumption from the grid and mini-PSPPs (four hydroturbines)
1	10800	0.07	0.14007	0.173096
2	10800	0.15	0.14007	0.173096
3	10800	0.23	0.14007	0.173096
4	21600	0.07	0.14007	0.154881
5	21600	0.15	0.14007	0.086548
6	21600	0.23	0.14007	0.086548
7	43200	0.07	0.14007	0.147475
8	43200	0.15	0.14007	0.053056
9	43200	0.23	0.14007	0.043274

The graph (Fig. 2.32) shows that the system without mini-PSPPs should be used for water flow intensity below 0.0926 m^3/sec with *E=21600 kWh*/day and 0.1259 m^3/sec with *E=43200 kWh*/day. In this case, in contrast to the basic tariff, the mini-PSPP system should not be applied to reduced power consumption below *E=13400 kWh*/day (for $\alpha_{ee} = 93.38\, UAH/MWh$ this limit is *E=20160 kWh*/day as in Fig. 2.21). 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%.

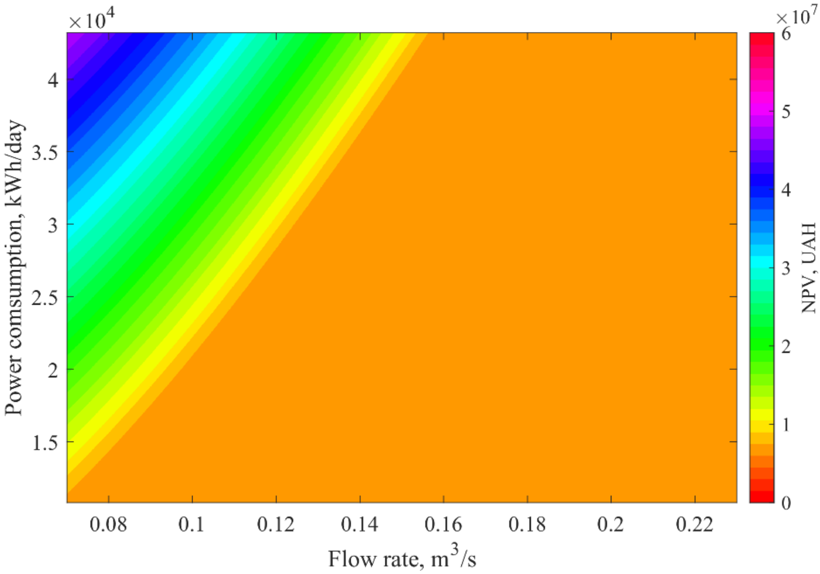

Figure 2.31 – Dependence $NPV = f\left(Q, E\right)$ for power system two hydroturbines introduced on the 500m level and two hydroturbines introduced on the 940m level with the tariff of $\alpha_{ee} = 140.07\, UAH/MWh$

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.

2.5. Generalization of the modelling results to assess effectiveness of the use of peak water-drainage-based PSPPs at iron ore underground mines

Analysis of various designs of consumers' power supply systems for conditions of a particular iron ore underground mine, in particular, installation of one or two hydroturbines on the 500 m level of and four hydroturbines –on the 500 m and 940 m levels of Rodina underground mine (Kryvyi Rih) demonstrate that peak PSPPs are most appropriate to use when the generated capacity is close to the installed capacity of consumers. At the same time, the use of various criteria for determining the most effective design of the power supply system demonstrates opposite results.

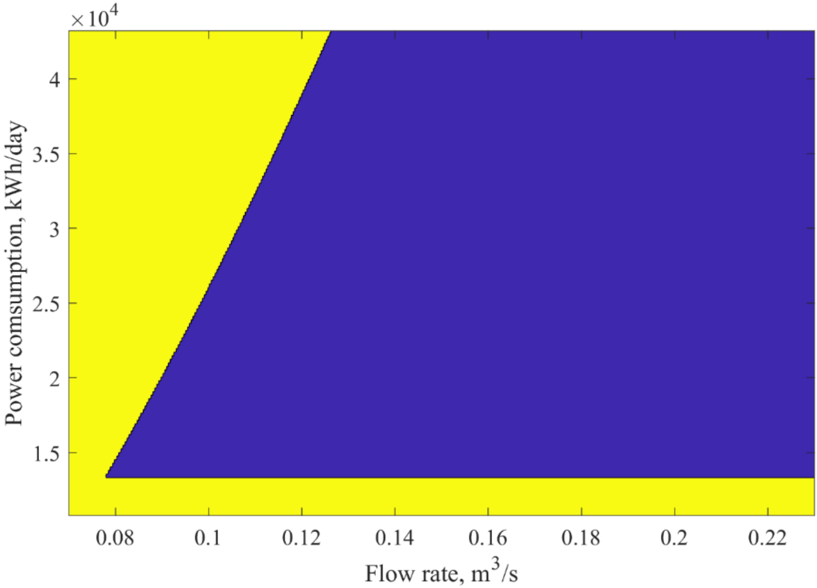

Figure 2.32 – Power system with four hydroturbines introduced on the 500m and 940m levels which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff of $\alpha_{ee} = 140.07\,UAH/MWh$

For example, from the point of view of the power cost, the most favourable conditions for introduction of the distributed generation system were demonstrated by installing one hydroturbine on the 500 m level. In this case, the net present value of power exceeds the current tariff for almost all considered operating conditions, except for very low water consumption through the pumping unit. This is due to the optimal ratio between, on the one hand, investments in the purchase of equipment of the peak PSPP, the cost of its maintenance and scheduled preventive maintenance, and, on the other hand, the level of meeting consumers' needs in generated power.

However, analysis of the NPV showed that under conditions close to nominal, the use of a peak PSPP with one hydroturbine has the highest present value due to the low level of generation, which makes it inexpedient to use compared to other designs.

The best option for implementation at the peak tariff is a system with a peak PSPP containing four turbines on the levels of 500 m and 940 m. It reveals the lowest NPV value in conditions close to nominal and the highest area of application within the considered limits of changes in power and water consumption through hydroturbines.

With the basic tariff, it is advisable to use a distributed generation system with only two hydroturbines on the 500 m level. It is of the highest value of application area among all the designs considered.

Thus, the greatest economic effect can be achieved by introducing a peak PSPP consisting of four hydroturbines, two of which are used during the hours of the basic tariff, and at other times when the peak tariff is used, all the units are involved. Such balancing should be implemented by the power supply management system of the mine consumers.

CONCLUSIONS

The analysis of the current state of power consumption by main water drainage facilities of iron ore undergroun mines suggests the absence of a systematic methodology for tracking the relevant processes. The comprehensiveness of the conducted research suggests the possibility and expediency of using the isolated groups of indicators as a system for assessing power consumption and cost for water drainage systems of iron ore mining enterprises.

The system-based analysis of the components for measurement and cost of consumed power by water drainage facilities gives grounds to propose a system of balanced quantitative indicators for assessing these indices at iron ore mining enterprises, including, the volume of power consumption, kWh; water flow; underground level, m; pump power, kW; the number of pumps, pcs.

The developed *ACS of power supply and consumption* of mining enterprises with an underground method of extracting iron ore raw materials with detailing in this structure of the subsystem of controlling the process of energy consumption of groundwater drainage complexes proposed in the course of research allows us to determine the guide for increasing the electrical energy efficiency of mining types of enterprises – the creation of a synergistic energy complex based on the mine water drainage.

The proposed methodology regarding the technology of development and functioning as part of the *ACS of electric power consumption of mining enterprises* of the water drainage control subsystem, has a unified structure and with the appropriate level of necessary adjustment can be used in other options for managing components power of enterprises, with a certain variability of input and output parameters, according to the corresponding research purpose, the subject of scientific research, set and formalized areas of scientific and practical search.

Studies have shown that main water drainage facilities of iron ore underground mines are ready-made or limitedly ready-made technological structures for development on their basis autonomous peak pump-storage power plants with the potential of power capacities sufficient to fully meet the energy needs of all power consumers – power receivers of a mining enterprise. The expediency of using peak PSPPs as part of the *ACS of power supply* is an example of distributed generation in power supply of mining enterprises' consumers. The use of such additional energy facilities that produce power allows increasing reliability and ensuring uninterrupted functioning of the power grids of these types of industrial enterprises. Subject to sufficient installed capacity of generating equipment PSPPs are able to ensure autonomous operation of the power grid in full for the required period of time.

It should be particularly noted that distributed generation of power creates prerequisites for flexible management of the "power supply-power consumption" complex of the mining enterprise due to local steering capacities. This approach reduces the dependence on fluctuations in the electricity tariff at different periods of the day, which is set by the company responsible for centralized power supply. All these factors ensure a reduction in the share of the energy component in the production cost of iron ore raw materials and minimize the negative impact on the operation mode of mining production from failures of centralized power supply.

The use of the energy potential of groundwater pumped out of working spaces of underground mines, in contrast to traditional renewable energy sources – sun and wind – has a number of positive features. The main one is their stable nature, which allows you to generate power exactly when needed, and not when there are atmospheric prerequisites for this. It also reduces the cost of such autonomous power plants due to the lack of need to create storage capacities based on secondary chemical current sources. The role of such conditional energy storage is played by tanks, which are already part of groundwater drainage facilities.

Also it is worth noting that features of mining production generally complicate insatllation of powerful generating equipment for wind or solar power plants inside or in close proximity to underground mines. Therefore, the use of peak PSPPs based on water drainage of iron ore underground mines becomes almost uncontested.

The next stage in improving power systems of mining enterprises, after the introduction of a system with autonomous power sources – distributed generation – is implementation of smart control algorithms for the "power supply-power consumption" complex using the Smart Grid concept. With this approach, control is carried out almost in real time, which ensures a quick response to changes in the state of the power system and allows you to optimize its operation depending on the current level of power consumption, potential volumes of the enterprise’s own generation and the current electricity tariff.

Implementation of the research results accompanied with the calculations of specialized enterprises for developing and implementing power supply systems in the practice of underground mining enterprises will allow obtaining an economic effect and ensure reliability and uninterrupted power supply of Ukraine’s strategic mining enterprises.

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Editor:

Sinchuk Oleh Mykolaiovych
D.Sc., Professor, Head of Department,
Department of Automated Electromechanical Systems in Industry and Transport,
Kryvyi Rih National University,
Kryvyi Rih, Ukraine

Authors:

Sinchuk Ihor Olehovych
PhD, Associate Professor,
Department of Automated Electromechanical Systems in Industry and Transport,
Kryvyi Rih National University,
Kryvyi Rih, Ukraine

Mykhailenko Oleksii Yuriiovych
PhD, Associate Professor, Head of Department,
Department of Power Systems and Energy Management,
Kryvyi Rih National University,
Kryvyi Rih, Ukraine

Budnikov Kyrylo Vsevolodovich
Postgraduate Student,
Department of Automated Electromechanical Systems in Industry and Transport,
Kryvyi Rih National University,
Kryvyi Rih, Ukraine

Sinchuk Ihor Olehovych
Mykhailenko Oleksii Yuriiovych
Budnikov Kyrylo Vsevolodovich

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Sinchuk Oleh Mykolaiovych
D.Sc., Professor, Head of Department,
Department of Automated Electromechanical Systems in Industry and Transport,
Kryvyi Rih National University,
Kryvyi Rih, Ukraine

Sinchuk Ihor Olehovych
PhD, Associate Professor,
Department of Automated Electromechanical Systems in Industry and Transport,
Kryvyi Rih National University,
Kryvyi Rih, Ukraine

Mykhailenko Oleksii Yuriiovych
PhD, Associate Professor,
Head of Department,
Department of Power Systems and Energy Management,
Kryvyi Rih National University,
Kryvyi Rih, Ukraine

Budnikov Kyrylo Vsevolodovich
Postgraduate Student,
Department of Automated Electromechanical Systems in Industry and Transport,
Kryvyi Rih National University,
Kryvyi Rih, Ukraine

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