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CALCULATION OF THE OPTIMAL HYDROPOWER UTILIZATION SYSTEM: A CASE STUDY OF A METALLURGICAL ENTERPRISE

Abstract. *Objective. This research is dedicated to the development, modeling, and optimization of a hydropower recovery system based on the reuse of secondary water resources within an industrial enterprise. The specific focus is on the graphitization workshop of PJSC "Ukrainian Graphite"–a metallurgical facility where substantial volumes of warm process water are discharged as a byproduct of production. The central objective of this study is to determine the optimal configuration of a water collection and energy conversion system that will enable efficient electricity generation at the lowest possible cost, while maintaining high energy performance. The task is conducted under the influence of strict technical and spatial constraints inherent to existing industrial infrastructure.*

Methodology. The study applies a set of engineering, mathematical, and economic methods. Hydraulic analysis is used to model water flow through both pressurized and gravity-fed pipelines, ensuring accurate determination of head losses and flow rates. A combinatorial optimization framework is employed to evaluate various topologies of system configurations, where water sources are matched with potential collection centers in the most effective way. A key feature of the methodology is the use of signature functions–a mathematical tool designed to define “prohibited zones” where placement of system elements is physically or operationally impossible due to safety, accessibility, or layout restrictions. These functions are integrated into the optimization model, enhancing the realism and applicability of the results. Additionally, a comprehensive techno-economic assessment is performed for each configuration, including calculations of capital expenditures, equipment cost, pipeline expenses, operational costs, and unit electricity production cost (LCOE).

Results. The modeling process revealed that the most economically and technically viable system involves a single collection center–Center No. 2–into which water flows from four

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main technological sources: електрокальцинатори (electric calciners), барабани-охолоджувачі (cooling drums), формувальна машина (molding machine), and підшипники димососів (smoke exhauster bearings). These flows are collected via a pipeline network with a total length of approximately 200 meters. The selected micro-hydropower plant (type 10Пр) is of a modular design and includes a діагональна турбіна (diagonal turbine). According to the calculations, this system is capable of generating over 135,000 kWh of electricity annually. The levelized cost of electricity (LCOE) is just US$0.30 per kWh, which is substantially lower than the applicable industrial electricity tariff in Ukraine. The total capital investment, including the cost of the micro-HPP unit, pipelines, installation, and commissioning works, is approximately US$168,800. Maintenance costs are estimated at 5% of capital expenditures annually.

Scientific novelty. The study introduces a new integrated methodology for assessing and designing hydropower recovery systems (HERS) at the local (workshop or facility) level, which takes into account technical parameters, hydraulic behavior, and spatial limitations. For the first time, the concept of signature functions is applied in this context to simulate constrained zones in system layout planning. This approach provides a flexible yet accurate mechanism for system designers to preclude impractical configurations early in the modeling phase, thereby saving resources and improving the efficiency of decision-making.

Practical significance. The developed methodology and the results obtained offer a practical solution for the sustainable use of internal water resources in energy-intensive industries. By implementing optimized HERS configurations, industrial enterprises can reduce dependence on external electricity supplies, enhance operational energy efficiency, and decrease total electricity costs. The approach also contributes to improved environmental performance by reducing heat discharge and enhancing water recycling. Furthermore, the proposed system architecture is modular and adaptable, allowing for scaling and replication in other industrial enterprises with similar infrastructure. This makes it especially relevant in the context of global trends toward decarbonization, resource efficiency, and green transformation of heavy industry.

Keywords: *hydropower recovery, secondary water resources, metallurgical enterprise, energy efficiency, micro-hydropower plant, hydraulic calculation, techno-economic assessment, optimization, signature function, collection center, water-energy nexus.*

Introduction

In the context of global challenges related to energy security, resource conservation, and the transition to a sustainable development model, there is an increasing demand for the rational use of all available energy sources, particularly secondary resources. One of the most promising areas in this field is hydropower utilization - the process of converting the potential of industrial technical water into useful electrical energy. This approach is especially relevant for energy-intensive industries such as metallurgy, where the volumes of circulating technical water are substantial, and its physical characteristics allow for the extraction of additional energy without relying on external sources.

According to research findings [1], the volume of technical water at metallurgical enterprises in the Zaporizhzhia region that can potentially be used as a hydropower resource amounts to approximately 66% of total water consumption. The cumulative flow power exceeds 1.0 MW, which is comparable to the capacity of small hydroelectric power plants installed on minor rivers. Utilization of this resource could generate up to 10 million kWh of electricity annually. Based on industrial electricity tariffs, this translates into annual savings of around US$9.24 million. These figures highlight not only the energy potential but also the economic feasibility of incorporating hydropower into the internal energy supply of an enterprise.

Unfortunately, despite the significant potential, most industrial enterprises do not exploit the possibility of converting secondary water flows into electricity due to a lack of adapted technical solutions, efficiency assessment models, and established engineering methodologies. The challenges include uncertainty in system configuration parameters (placement of collection centers, pipeline routing), lack of consideration for specific operating conditions (restricted zones, technological constraints), and underdeveloped methods for calculating the hydraulic and energy characteristics of the system.

In the current era of technological advancement, where advanced digital modeling tools, mathematical analysis, and engineering visualization are readily available, there is a pressing need to integrate these instruments into the design process of utilization systems. Particularly relevant is the use of combinatorial

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optimization, algorithms for evaluating pipeline topology, and spatial modeling methods employing signature functions to define equipment placement constraints. This approach enables not only technically feasible system design but also the identification of the most economically viable options.

Moreover, the utilization of secondary hydropower resources offers a range of additional benefits:

– reduction of the load on the general power supply system of the enterprise;
– decreased reliance on expensive external energy sources;
– increased energy autonomy of production processes;
– improved ecological balance through reduced thermal losses in wastewater;
– lower greenhouse gas emissions due to the shift toward renewable energy.

Therefore, the implementation of hydropower utilization systems at metallurgical enterprises is not only an economically justified solution but also a step toward sustainable development, aligned with both national and global "green" transformation trends.

In this context, the aim of the present study is to calculate the optimal system for utilizing secondary hydropower resources at a metallurgical enterprise, using the graphitization shop of PJSC "Ukrainian Graphite" as a case study. The work involves a comprehensive examination of configuration and hydraulic parameters, as well as the economic justification of system variants, to determine the most efficient techno-economic solution for practical implementation.

Problem Statement. The aim of this study is to calculate the optimal system for the utilization of secondary hydropower resources at a metallurgical enterprise, using the graphitization shop of PJSC "Ukrainian Graphite" as a case study.

Main Research Section. At the selected industrial facilities, significant volumes of technical water are available. After being used in production processes, these water flows are discharged by gravity to lower levels. The elevation differences between these levels can reach several tens of meters, and even with relatively low water flow rates, the calculated hydropower potential proves to be considerable [2].

For more precise and objective analysis, it is advisable not to treat the enterprise as a monolithic unit but rather to disaggregate it into its structural components–namely, individual workshops or production sections. This modular approach allows for a more detailed and localized assessment of the technical and hydraulic parameters relevant to each unit, taking into account their unique configurations, equipment layouts, and specific water usage profiles.

By conducting detailed evaluations of each individual workshop within an industrial facility, it becomes feasible to uncover and analyze localized sources of secondary water flows–those generated as a byproduct of various technological processes such as cooling, washing, and heat exchange. Each of these sources can be characterized in terms of its flow rate, temporal variability, pressure head, and thermal characteristics, allowing for a more precise understanding of their potential for hydropower recovery. Unlike traditional enterprise-wide assessments, this disaggregated approach facilitates a more nuanced, site-specific analysis that aligns with the complex operational dynamics and physical layout of the facility.

The ability to isolate and assess each workshop separately enables the design and implementation of customized hydropower recovery solutions tailored to the specific hydraulic and spatial parameters of that zone. For example, a workshop with high flow and moderate pressure may be well-suited for installing a micro-hydropower plant (micro-HPP) with a radial or diagonal turbine, while another section with low flow but high head may require a different turbine configuration or energy conversion approach. This level of detail is critical in ensuring the technical feasibility and cost-effectiveness of the system, as well as in avoiding the risk of underutilization or overdesign of equipment.

Furthermore, the use of this methodology significantly enhances the precision of engineering calculations. It reduces the potential for overgeneralization, which is a common limitation in large-scale energy audits where heterogeneous water flows are averaged across the facility. By focusing on discrete zones, engineers can more accurately model energy losses, frictional resistance, and localized head drops. Moreover, this approach facilitates the consideration of spatial constraints, such as equipment accessibility, safety zones, prohibited installation areas (which may be defined using signature functions), and technological interdependencies between subsystems.

By accounting for such factors at the workshop level, the methodology enables the development of technically sound and economically rational hydropower

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recovery solutions that can be seamlessly integrated into existing operations. The aggregated outcome of individually optimized subsystems provides a robust foundation for estimating the overall energy recovery capacity of the enterprise. This, in turn, supports long-term strategic planning, allowing decision-makers to prioritize investments based on energy return, payback period, and integration costs.

In addition, phased implementation strategies can be developed, beginning with the workshops that offer the highest return on investment or that are easiest to retrofit. As more workshops are integrated into the overall hydropower recovery system, the enterprise gradually moves toward energy self-sufficiency, operational resilience, and reduced environmental impact. Such a modular, scalable approach also allows for adjustments over time in response to changes in production processes, water usage patterns, or external energy market conditions.

Ultimately, the disaggregated analytical approach not only results in more accurate, feasible, and site-specific engineering outcomes, but also creates a data-driven framework for decision-making. It supports the adoption of sustainable energy practices in heavy industry, promotes resource efficiency, and enables enterprises to meet regulatory and environmental targets. In the context of global efforts toward decarbonization and circular economy implementation, this methodology represents a forward-looking tool for achieving both operational excellence and long-term sustainability.

As an example of a hydropower utilization object, the graphitization shop of PJSC "Ukrainian Graphite" was selected. The following equipment is located within its territory: electric calciners, cooling drums, smoke exhauster bearings, a molding machine, and cooling systems - all of which serve as sources of secondary water, with flow rates ranging from 20 to 50 m^3/h. The elevation at which water is discharged varies from 4.8 to 17.1 meters.

From a technical standpoint, considering the presence of other technological equipment and auxiliary infrastructure on the shop floor, the placement of water collection centers is feasible only at three specific points. Moreover, the aforementioned equipment is located in so-called "restricted zones," i.e., areas where the installation of hydropower system elements (HPS) is not permitted. As defined in [3], the spatial constraints of such zones are modeled in the form of parallelepipeds, and the simplest analytical representation of these zones is achieved using a signature function.

The key characteristics of the site, which serve as the input data for the optimization of the hydropower utilization system, are summarized in Table 1.

Table 1

Characteristics of Secondary Water Sources

Water Source	Coordinates of Secondary Water Sources (x; y; z), m	Maximum Flow Rate Q_{max}, m³/h	Head, m	Coordinates of Collection Centers (x; y), m
Electric Calciners	23.5; 55; 19 36.5; 55; 19 49.5; 55; 19 62.5; 55; 19 75.5; 55; 19 88.5; 55; 19	50	17.1	105; 55
Cooling Drums	21.75; 41.5; 6 34.75; 41.5; 6 47.75; 41.5; 6 60.75; 41.5; 6 73.75; 41.5; 6 86.75; 41.5; 6	30	5.0	95; 32
Molding Machine	65; 28; 11	20	10.0	25; 10
Smoke Exhauster Bearings	108; 26; 6 108; 23; 6 108; 20.5; 6 108; 17.5; 6 108; 14; 6	28.8	4.8	–

Note: Overall dimensions of the facility (shop floor) – 115 × 60 × 22 m.

At the first stage of the computational procedure, the primary focus is placed on determining the characteristics of an optimal hydropower utilization system (HPUS) under the assumption of a conditionally constant maximum water flow rate. This means that the dynamic fluctuations in flow rates–such as temporal variations due to production cycles, equipment downtime, or cleaning procedures–are not initially considered. Instead, the system is analyzed based on peak operating conditions that reflect the highest expected water discharge levels from each source.

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This simplification enables the creation of a baseline model, providing a foundation for understanding the system’s theoretical maximum capacity for energy recovery.

Under this assumption, the analysis involves systematically identifying all feasible combinations of linking the available secondary water sources, denoted as nnn, with the potential water collection centers, denoted as mmm, across the facility. Each pairing represents a possible configuration in which the hydraulic potential of one or more water sources can be routed to a designated collection point for energy conversion. The combinatorial nature of this task is non-trivial, particularly in facilities where numerous sources and collection points exist, as the number of potential configurations grows exponentially with system complexity.

To ensure completeness, all technically admissible pairings are enumerated using combinatorial algorithms, which take into account geometric feasibility (e.g., shortest pipeline path), pressure losses due to friction, elevation differences, and the presence of spatial or structural constraints. The goal of this step is to construct a comprehensive solution space that encompasses every possible linkage scenario under steady-flow conditions. Each configuration is then evaluated in terms of its hydraulic performance–specifically, the available head, flow capacity, and anticipated energy output–using classical fluid dynamics equations such as the Bernoulli and Darcy-Weisbach formulations.

Additionally, this stage of analysis allows for the preliminary sizing of micro-hydropower units (micro-HPPs) based on the estimated energy recovery potential at each collection center. By simulating each pairing independently, the research identifies optimal routing paths and suitable turbine types, considering whether radial, axial, or diagonal turbines would yield the highest efficiency for a given flow/head combination. The simplification to constant flow conditions not only streamlines the initial analysis but also establishes a robust framework that will later accommodate dynamic flow modeling.

While this initial model does not yet reflect real-time variability in water discharge patterns, it serves as a necessary starting point for optimization. It allows the research team to narrow down the most promising system topologies before introducing more complex variables in subsequent modeling phases, such as time-dependent flow variations or stochastic input data. Ultimately, the findings from this stage inform both the technical layout and the economic feasibility of various HPUS configurations, providing a valuable decision-making tool for early-stage project planning and investment assessment.

In this case, the total number of possible combinations is equal to [4–6] (to be specified with a formula or value), which serves as the initial solution set for further optimization aimed at minimizing costs or head losses: $r = m^n$.

For the first combination, the distribution of sources among the collection centers (CC) was carried out as follows:

CC No. 1 – electric calciners;

CC No. 2 – smoke exhauster bearings, cooling drums, molding machine;

CC No. 3 – no sources assigned.

The required diameter of the pipeline from electric calciners No. 1–6 to Collection Center No. 1, ensuring the necessary flow capacity, was calculated using the following formula [7]:

$$d_{\kappa r} = 2\left(\frac{Q_{\kappa,\max}}{\pi \cdot \upsilon_{\kappa}}\right)^{0,5}, \tag{1}$$

where $Q_{k,max}$ – is the value of the maximum flow rate for the given source; v_k – is the fluid velocity in the pipeline. For non-pressurized flow, the water velocity is v_k = 0.1...0.3 m/s, and for pressurized flow, it is v_k = 1.1...1.3 m/s [8].

Based on the calculated diameter d_{kr}, the next larger standard pipeline diameter is selected.

Next, the distance l_{kr} between sources k and collection centers p is determined using their given coordinates. According to the algorithm developed in [9], the shop floor space is divided into cubes with a total number of nodes at their vertices (points for laying pipeline routes):

$$l_{\kappa p} = \left[\left(x_{\kappa} - x_p\right)^2 + \left(y_{\kappa} - y_p\right)^2 + \left(z_{\kappa} - z_p\right)^2\right]^{0,5}, \tag{2}$$

where x_κ, y_κ, z_κ, x_p, y_p, z_p – coordinates of the sources and collection centers, respectively; Δ – the coordinate increment step is assumed to be Δ = 1 m.

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The set of possible pipeline routing paths, passing through the nodes obtained in this way, is generated at the next step. As a result of filtering out routes whose points fall within the restricted zones of the j-th equipment of the IESU (Integrated Energy Supply Unit), using a signature function, it was determined that the shortest path has a length of 83.7 meters.

Then, the characteristics of the fluid flow in the pipeline are determined. Water flow velocity:

$$\upsilon_л = \left(\frac{8g}{\lambda}\cdot R\cdot i\right)^{0,5}, \tag{3}$$

where $\left(\frac{8g}{\lambda}\right)^{0,5} = C$ – the Chezy coefficient (determined using Pavlovsky’s formula [8]: when 0,1 < R < 3 m, then $C = R^y/n$, $y = 2{,}5\, n^{0,5} - 0{,}13 - 0{,}75\, R\cdot(n^{0,5} - 0{,}1)$, n – roughness coefficient, n = 0,013, R – hydraulic radius, $R = \omega/\chi$, ω – cross-sectional area of the flow, χ – wetted perimeter, i - hydraulic gradient.

The cross-sectional area of the flow is defined as:

$$\omega = 0,785\, d_{кр}^{\,2}\cdot\frac{\phi}{2\pi} + 0,5\left(h - \frac{d_{кр}}{2}\right)\cdot 2\left[\left(\frac{d_{кр}}{2}\right)^2 - \left(h - \frac{d_{кр}}{2}\right)^2\right]^{0,5}, \tag{4}$$

where φ – the angle formed between the longitudinal axis of the pipeline and the tangent point of the free surface of the water, h – flow depth in the pipe.

The total head loss in the pipeline H_{loss} consists of local losses $\sum h_м$ and H_l linear losses:

$$H_{loss} = \sum h_м + H_l\,. \tag{5}$$

Head losses along the length of the pipeline are determined using the following formulas:

$$H_{l,кр} = \lambda\cdot\frac{l_{кр}}{d_{кр}}\cdot\frac{\upsilon_к^2}{2g}, \tag{6}$$

$$H_{l,кр} = \frac{\upsilon_к^2\cdot l_{кр}}{C^2\cdot K}, \tag{7}$$

where λ – the hydraulic friction coefficient, which accounts for all factors influencing head loss along the length of the pipeline – primarily the fluid viscosity and the condition of the pipe walls – according to the formula by A.D. Altshul [8]: $\lambda = 0{,}11(\kappa_e / d + 68 / Re)^2$, κ_e – equivalent sand-grain absolute roughness.

During hydraulic calculations of both pressurized and gravity flow networks, local head losses are considered and determined using the Weisbach formula [8]:

$$h_м = \zeta \times \frac{\upsilon^2}{2g}, \tag{8}$$

where ζ – the local resistance coefficient, which depends on the Reynolds number

The hydraulic power of the secondary water source $N_{\kappa\gamma}$ taking into account energy losses in the elements of the collection system, it is determined as:

$$N_\gamma = \sum_{p=1}^{q} N_{p\gamma}. \tag{9}$$

After determining the parameters of the total secondary water flow entering Central Node No. 1 from the electrocalcinators, equipment for hydropower recovery is selected, namely a modular-type micro-hydropower plant (micro-HPP). For the above-mentioned flow characteristics, a unit of type 20 PrD with a diagonal-type turbine is selected. The nominal flow rates range from 0.08 to 0.17 m^3/s, heads from 8.0 to 18.0 m, and power from 10.0 to 20.0 kW.

The energy generated by the micro-HPP generator is determined using the formula [10]:

$$W_p = N_p \cdot T \cdot \eta_{рт} \cdot \eta_{рг}, \tag{10}$$

where T – the enterprise's working time fund (for a three-shift schedule) is equal to 8,760 hours, $\eta_{рт}$ and $\eta_{рг}$ – the efficiency of the turbine and generator, respectively.

The capital investments for generating electricity from the given water flow will consist of the costs for the micro-HPP energy module, connecting pipelines, and the cost of installation and routine maintenance works. The cost of installation and commissioning works in this case amounts to 7.5%, while the cost of routine repairs

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and maintenance of fixed assets is 5% of the capital expenditures. The cost of the 20 PrD-type micro-HPP produced by MNTO 'INSET' is US$183 thousand. The specific cost of a 325 mm diameter pipeline, according to BMU 'Zaporizhstalbud-1', is US$661,992/km.

For Central Node No. 2, the following technical and economic indicators are obtained: the cost of the 10 Pr-type micro-HPP, which is used for the energy recovery from the total water flow with the following parameters Q_Σ = 96 m^3/sec and H_Σ = 5,2 m amounts to US$102.4 thousand, while the capital expenditures total US$159.75 thousand and, accordingly, the operating costs are US$7.15 thousand. The annual amount of electricity generated is 34,256 kWh.

The cost price of electricity (CEE) produced by the entire hydropower energy recovery system is determined using the following formula:

$$C_{EE} = \frac{K_n}{W} , \tag{11}$$

where K_n – operating costs, $K_n = \sum_{p=1}^{q} K_{nq}$; W – the amount of electricity generated over time T, $W = \sum_{p=1}^{q} W_p$.

As a result of computational operations based on the above algorithm, the characteristics of all possible topology variants of the hydropower energy recovery system (HERS) for the considered facility were determined. These variants are defined by combinations of secondary water sources connected to hydropower collection centers, taking into account constraints on the location of system elements. Some of the variants, for which the cost price of electricity generation does not exceed the established grid tariff C ≤ Cм for industrial enterprises as of 01.11.2011 – US$0.9237 /(kWh) [11]), the relevant data are presented in Table 2.

It is evident that when determining the optimal hydropower energy recovery system (HERS), the most economically advantageous topology variant is selected based on economic criteria. That is, the following condition must be met: the amount of electricity generated through hydropower recovery must be as high as possible, while its cost price must not exceed the current electricity tariff for the given industrial enterprise.

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It was established that the most economically efficient system consists technically of secondary water sources connected via pipelines to Collection Center No. 2 (Figure 1). Collection Centers No. 1 and No. 3 remain unused.

Thus, the anticipated total capital investment in the optimal HERS for the given hydropower recovery facility amounts to US$168,817.59, with the cost price of electricity being US$0.30/(kWh), based on the equipment and installation and maintenance costs valid as of 01.11.2021.

Table 2

Technical and Economic Indicators of Hydropower Recovery Projects for the Graphitization Workshop of PJSC "Ukrainian Graphite"

Option No.	Electricity Generation, thousand (kWh/year)	Electricity Cost Price, US$/(kWh)
1	135.153	0.28
2	135.200	0.28
3	135.169	0.29
4	134.927	0.29
5	135.054	0.29
6	134.948	0.29
7	134.984	0.29
8	134.626	0.29
9	134.594	0.29
10	135.169	0.29
11	135.216	0.297
12	135.195	0.31
13	134.911	0.32
14	134.885	0.35
15	134.932	0.63
16	134.340	0.72
17	132.139	0.91

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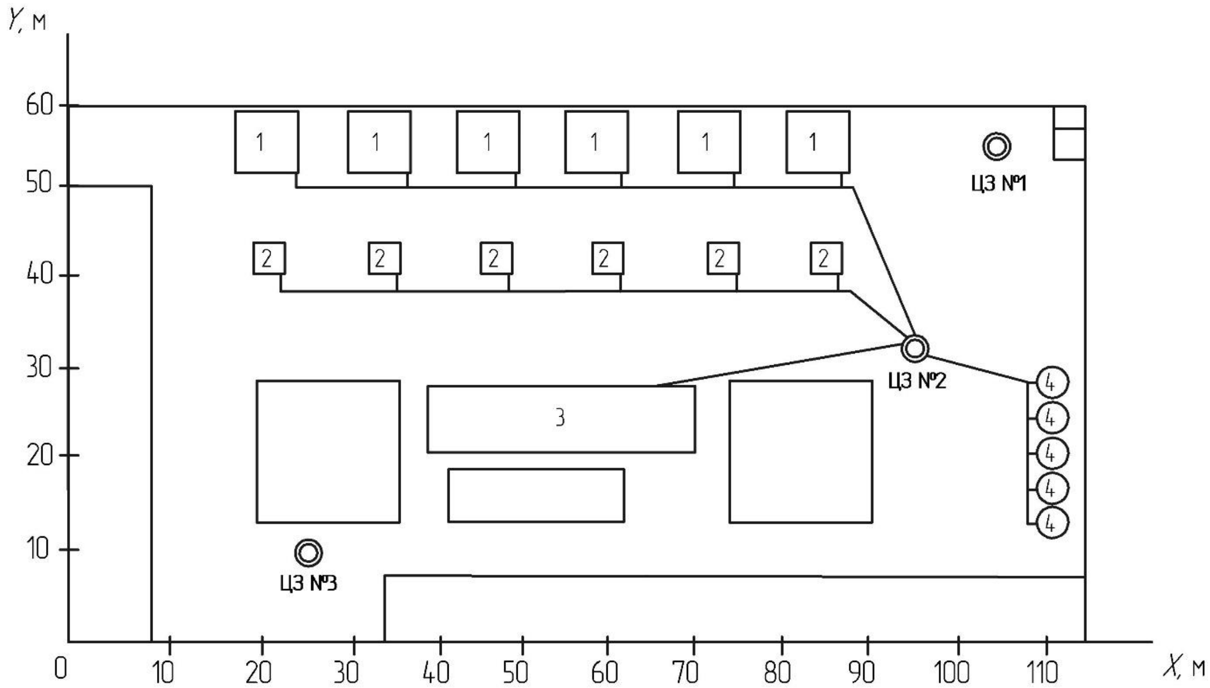

Figure 1 – Equipment layout of the graphitization workshop showing the economically optimal hydropower energy recovery system (HERS)
1 – Electrocalcinators; 2 – Cooling drums; 3 – Molding machine;
4 – Induced draft fan bearings.

The main parameters of the elements of the optimal water resource collection system and the equipment for hydropower recovery are summarized in Table 3.

Table 3

Parameters of the equipment in the optimal HERS for the graphitization workshop of PJSC "Ukrainian Graphite"

Collection Center – Source		Pipeline Diameter d, m	Length l, m	Micro-HPP Type
№ 1	Not used			
№ 2	Electrocalcinators	0.325	76.12	10Pr
	Cooling drums	0.273	73.83	
	Molding machine	0.076	31.06	
	duced draft fan bearings	0.219	22.29	
№ 3	Not used			

Conclusion

Calculations conducted using the example of a metallurgical industrial enterprise have clearly demonstrated that the technical and economic performance of secondary hydropower recovery systems can vary substantially depending on several key factors. Among the most influential variables are the structural configuration of the water collection network, the spatial topology of the placement of electricity-generating equipment, and the associated capital costs for installation, commissioning, and integration of system components into existing infrastructure.

A detailed analysis of multiple system topology variants has shown that even minor changes in the pipeline layout or the selection of the water sources for recovery can lead to noticeable differences in electricity output, system efficiency, and cost-effectiveness. These differences are further magnified by fluctuations in the prices of construction materials, labor, and energy equipment. Furthermore, the cost of routine maintenance, as well as operational reliability and accessibility for servicing, also significantly affect the overall viability of a given hydropower recovery project.

The study confirms that a properly designed and optimized hydropower energy recovery system, based on accurate hydraulic and economic calculations, can become a valuable component of an industrial enterprise's energy strategy. By utilizing secondary water flows–often considered waste in traditional industrial processes–such systems offer an opportunity to produce renewable, localized electricity with relatively low operational costs. This not only offsets the consumption of grid electricity but also aligns with broader environmental and sustainability goals by reducing dependency on fossil fuels and minimizing waste.

In addition to reducing energy bills, the implementation of such systems contributes to greater energy security and operational autonomy. For industries with high and stable water usage profiles, such as metallurgy, chemical processing, or food production, integrating hydropower recovery into production workflows can significantly improve long-term financial outcomes and reduce vulnerability to fluctuations in electricity tariffs.

Therefore, the introduction of secondary hydropower energy recovery systems–when approached with careful consideration of hydraulic dynamics, equipment efficiency, and economic optimization–is not only technically achievable but also economically justified. It offers a pathway to enhance the sustainability and

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competitiveness of industrial enterprises, facilitating their transition toward more energy-resilient and environmentally responsible operations.

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РОЗРАХУНОК ОПТИМАЛЬНОЇ СИСТЕМИ ГІДРОЕНЕРГЕТИЧНОЇ УТИЛІЗАЦІЇ: ПРИКЛАД МЕТАЛУРГІЙНОГО ПІДПРИЄМСТВА

Анотація. *Мета. Метою даного дослідження є розрахунок оптимальної системи утилізації вторинних гідроенергетичних ресурсів на прикладі цеху графітації металургійного підприємства ВАТ «Український графіт». Основним завданням є* *визначення такої конфігурації системи збору та перетворення гідроресурсів, яка дозволяє мінімізувати собівартість виробленої електроенергії та забезпечити енергоефективність підприємства з урахуванням наявних технічних і просторових обмежень.*

Методика. У дослідженні використано методи гідравлічного розрахунку, комбінаторну оптимізацію, сигнатурні функції для моделювання обмежень, а також техніко-економічний аналіз для оцінки ефективності різних конфігурацій систем збору гідроресурсів.

Результати. Визначено параметри оптимальної системи гідроенергетичної утилізації для конкретного об'єкта. Встановлено, що найбільш економічно доцільним є варіант із використанням лише одного центру збору (ЦЗ № 2), при загальній довжині трубопроводів близько 200 м. Річне вироблення електроенергії перевищує 135 тис. кВт·год, а собівартість становить 0,30 US$ /кВт·год, що значно нижче чинного тарифу. Орієнтовні капітальні витрати на обладнання (мікро-ГЕС типу 10Пр) та інфраструктуру становлять US$ 168,8 тис.

Наукова новизна. Запропоновано нову методику оцінки ефективності системи утилізації гідроенергетичних ресурсів (СГЕУ) на рівні окремого промислового цеху з урахуванням технічних обмежень і просторових характеристик. Уперше застосовано сигнатурну функцію для опису «заборонених зон» у розміщенні обладнання.

Практичне значення. Розроблена методика дозволяє точно та ефективно планувати системи утилізації енергетичного потенціалу вторинних вод на промислових підприємствах. Це сприяє підвищенню енергонезалежності, зниженню витрат на електроенергію, покращенню екологічних показників і раціональному використанню ресурсів. Отримані результати можуть бути адаптовані до інших підприємств із подібною інфраструктурою.

Ключові слова: *гідроенергетична утилізація, вторинні водні ресурси, металургійне підприємство, енергоефективність, мікро-ГЕС, гідравлічний розрахунок, техніко-економічне обґрунтування, оптимізація, сигнатурна функція, центр збору.*

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