

УДК 697.34

**ANALYSIS OF THE EFFICIENCY OF DISTRICT HEATING NETWORKS AFTER
BOILER HOUSE MODERNIZATION UNDER A REDUCED TEMPERATURE REGIME**

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**АНАЛІЗ ЕФЕКТИВНОСТІ ФУНКЦІОНУВАННЯ ТЕПЛОВИХ МЕРЕЖ ПІСЛЯ
МОДЕРНІЗАЦІЇ КОТЕЛЬНІ ПРИ ЗНИЖЕНОМУ ТЕМПЕРАТУРНОМУ ГРАФІКУ**

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DOI: <https://doi.org/10.18664/1994-7852.217.2026.371597>



Abstract. The article examines the modernization of a boiler house and the transition to a reduced-temperature operating schedule of the heating networks of a school located in the Kharkiv district. The economic efficiency of transitioning to a fourth-generation district heating system is considered through the change from a 95/70 °C temperature schedule to a 55/40 °C temperature schedule. A comparison of hydraulic and thermal losses in heating networks constructed from steel and non-metallic pipelines is carried out. Methods for reducing the heat carrier flow rate in heating networks are also considered.

Keywords: district heating system, heat carrier flow rate, thermal losses, hydraulic losses, energy efficiency, thermal modernization, heating networks.

Анотація. У статті розглянуто питання модернізації котельні та переходу теплових мереж закладу загальної середньої освіти, розташованого в Харківському районі, на

ISSN (p) 1994-7852

ISSN (online) 2413-3795

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Панчук О. В., Авакян К. О., 2026.

знижений температурний графік теплопостачання. Особливу увагу приділено впровадженню принципів систем теплопостачання четвертого покоління, що передбачають підвищення енергоефективності, зменшення теплових втрат, оптимізацію гідравлічних і температурних режимів і підвищення надійності роботи системи теплопостачання.

Метою дослідження є визначення технічної та економічної доцільності модернізації системи теплопостачання освітнього закладу через зниження температури теплоносія та застосування сучасних енергоефективних технологій. Досліджено економічну доцільність переходу від традиційного температурного графіка 95/70 °C до низькотемпературного графіка 55/40 °C. Проаналізовано вплив зниження температури теплоносія на витрати паливно-енергетичних ресурсів, гідравлічні параметри мережі та експлуатаційні показники системи теплопостачання.

У роботі проведено порівняльний аналіз гідравлічних характеристик і теплових втрат теплових мереж, виконаних зі сталевих і неметалевих трубопроводів. Оцінено вплив матеріалу трубопроводів, їхніх діаметрів і теплоізоляційних характеристик на величину втрат тиску, теплові втрати, довговічність і надійність експлуатації мереж у низькотемпературних режимах роботи. Розглянуто можливість використання сучасних попередньо ізольованих трубопроводів як одного з напрямів підвищення енергоефективності системи.

Також визначено основні шляхи зниження витрат теплоносія в теплових мережах, зокрема за рахунок термомодернізації будівлі, оптимізації гідравлічних режимів, застосування сучасного насосного обладнання з частотним регулюванням, балансування системи теплопостачання та використання енергоефективних трубопроводів із покращеними теплоізоляційними характеристиками. Запропоновані технічні рішення спрямовані на скорочення експлуатаційних витрат, підвищення енергоефективності та забезпечення стабільної роботи системи теплопостачання.

Ключові слова: система теплопостачання, витрати теплоносія, теплові втрати, гідравлічні втрати, енергоефективність, термомодернізація, теплові мережі.

Introduction. The heat supply system is one of the key elements of engineering infrastructure that ensures the delivery of thermal energy to residential, public, and industrial facilities. The efficiency of its operation depends on a combination of technical and operational factors, among which the hydraulic regime plays a decisive role, as it directly ensures the reliability, stability, and economic efficiency of heating network operation.

The hydraulic regime is understood as a set of parameters characterizing the distribution of pressure and heat carrier flow rate within the system, which directly affect the level of energy losses and the quality of heat supply provided to consumers. Disruptions in hydraulic balance lead to a reduction in the efficiency of thermal energy transportation, an increase in thermal and hydraulic losses, higher electricity

consumption by pumping equipment, as well as an uneven temperature distribution throughout the network. As a result, this causes an increase in operating costs and a decrease in the overall energy efficiency of the heat supply system [1].

Analysis of recent research and publications. Among the current directions for improving the efficiency of heating networks, the implementation of reduced heat carrier supply temperature regimes occupies an important place. Traditional heat supply systems operating under high-temperature schedules are associated with significant thermal losses during heat carrier transportation and limit the possibilities for integrating alternative energy sources. In contrast, the use of low-temperature operating regimes, particularly with supply temperatures below 65 °C or around 50 °C, makes it possible to significantly reduce heat losses in the networks,

decrease operating costs, and improve the overall energy efficiency of heat supply systems [2].

Low-temperature heat supply systems are characterized by several additional advantages. First, reducing the temperature difference between the heat carrier and the surrounding environment contributes to lower thermal losses in pipelines [3]. Furthermore, such systems create favorable conditions for the integration of renewable and secondary energy sources, including geothermal installations, solar collectors, and industrial waste heat recovery technologies [4]. The operation of heat pumps under low-temperature conditions is also more efficient, as their performance is optimized under reduced heat carrier temperatures [5]. Additionally, this may contribute to lower operating costs for pumping equipment and other network components due to less stringent requirements for pressure and temperature parameters [6].

In the strategic context of decarbonizing the heating and cooling sector of the European Union by 2050, the development of fifth-generation district heating and cooling systems has been identified as an important direction. Such networks operate under low-temperature conditions, forming so-called “cold” thermal systems characterized by the extensive use of renewable energy sources and providing opportunities for bidirectional heat and cooling exchange within urban energy infrastructure [7].

At the same time, reducing the heat carrier temperature is accompanied by an increase in its flow rate, which, in turn, leads to higher hydraulic losses, the need for selecting pumping equipment of appropriate sizes, adjustments to pipeline diameters, and rebalancing of the heat supply system.

For Ukraine, the issue of improving the efficiency of heat supply systems is particularly relevant, as it is associated with strategic objectives of reducing energy consumption, decreasing dependence on conventional fuel and energy resources, and adapting heating networks to the principles of sustainable

development. In this context, national regulatory and legal acts define criteria for assessing the efficiency of thermal energy transportation, including the level of heat losses in networks, specific water consumption, and electricity consumption, all of which directly depend on the hydraulic operating regime of the heat supply system [8].

Calculations of heat losses in heating networks, as well as methods for their determination, are presented and discussed in detail in studies [9, 10, 11]. Certain aspects of transitioning the heating networks of the city of Kharkiv from traditional temperature schedules of 150–70 °C and 135–70 °C to reduced schedules of 124–61 °C and 118–59 °C are comprehensively examined in study [12].

Goal and task setting. The primary objective of this study is to determine the level of reduction in fuel and energy resource consumption resulting from boiler house modernization and the transition of heating networks to operation under a reduced temperature schedule. Particular attention is paid to assessing the impact of low-temperature heat supply regimes on system energy efficiency, reducing heat losses in the networks, decreasing heat carrier consumption, and improving the operational efficiency of boiler and pumping equipment.

The study also considers various pipeline options for heating networks, including pre-insulated steel pipes and non-metallic pipelines with factory-manufactured thermal insulation. An analysis of their technical and operational characteristics was carried out, particularly hydraulic parameters, thermal losses, durability, operational reliability, and the economic feasibility of their application under low-temperature heat supply conditions.

In addition, the study examines the possibilities of reducing heat carrier flow rate as one of the principal approaches to minimizing hydraulic losses in heating networks. The impact of optimizing heat carrier flow rate on reducing pressure losses, lowering electricity consumption by pumping equipment, and improving the overall energy

efficiency of the heat supply system is also investigated.

The main part of the study. For the purposes of this study, a general secondary school located in the Kharkiv district was selected, with an existing heating system thermal load of 0,22 Gcal/h. Centralized domestic hot water supply is absent at the facility. The heat source is a local gas-fired boiler house located on the school premises, where two gas-fired NIISTU-5 boilers are installed (one operating unit and one standby unit), each with a thermal capacity of 300 kW and an actual efficiency of 75 %. The existing temperature schedule for qualitative regulation of the heat supply system is 95/70 °C. The heat supply system is a two-pipe system, with water used as the heat carrier.

The heating network from the boiler house to the school building is constructed of steel pipelines with a diameter of 133×4.0 mm, insulated with mineral wool slabs, and has a total length of 59.6 m. The heating networks are installed underground using a trenchless (channel-free) laying method.

Within the framework of this study, boiler house reconstruction is proposed, including the replacement of the existing NIISTU-5 boilers with modern condensing boilers, Vitocrossal 300 type CI3, manufactured by Viessmann [13], with an efficiency of 97,7 %. In addition, the replacement of the existing network pumps Wilo TOP-S 40/7 (two units: one operating and one standby) with modern energy-efficient Wilo Stratos MAXO 50/0,5-9 variable-speed pumps manufactured by Wilo [14] is planned.

A reduction of the temperature schedule to 55/40 °C is also proposed, which corresponds to the objectives of sustainable development, improvement of energy efficiency in heat supply systems, and transition toward fourth-generation district heating systems.

The study considers a comparison between the existing configuration of the heat source and heating networks and two new alternatives, taking into account boiler house

modernization and heating network reconstruction: the first alternative involves the use of factory-manufactured pre-insulated steel pipelines with a diameter of 114/200×4.0 mm [15], while the second alternative involves replacing steel pipes with non-metallic pre-insulated pipelines with factory-manufactured thermal insulation, having a diameter of 110/182×10 mm [16]. A comparative analysis of the technical, thermal engineering, and hydraulic characteristics of these heating network alternatives is carried out.

In total, three system alternatives are considered:

Alternative 1 – the existing heat supply source and heating networks, operating under a temperature schedule of 95/70 °C;

Alternative 2 – a modernized boiler house operating under a temperature schedule of 55/40 °C, combined with reconstruction of the heating network using factory-manufactured pre-insulated steel pipelines with a diameter of 114/200×4.0 mm;

Alternative 3 – a modernized boiler house operating under a temperature schedule of 55/40 °C, combined with reconstruction of the heating network using factory-manufactured non-metallic pre-insulated CALPEX PURKING UNO pipelines with a diameter of 110/182×10 mm.

The specified alternatives will be compared in terms of thermal and hydraulic losses, gas consumption, and an analysis of operating costs during the heating period expressed in monetary terms will also be carried out.

Comparison of Heat Losses During the Heating Period

The specific heat losses are determined using the following equation, W/m:

$$q = \frac{T_{avg} - T_{gr}}{r_{tot}}, \quad (1)$$

where T_{gr} – average ground temperature during the heating period, °C;

T_{avg} – average heat carrier temperature during the heating period, °C;

r_{tot} – total thermal resistance, m·°C/W.

The total thermal resistance of the insulation layer and other additional thermal resistances along the heat flow path is determined as:

$$r_{tot} = \frac{\ln B}{2 \cdot \pi \cdot \lambda_k} + \frac{1}{a_e \cdot \pi \cdot (D_{out} + 1)}, \quad (2)$$

where λ_k – thermal conductivity of the thermal insulation layer, W/(m·°C), assumed as 0,027 for steel pipes with polyurethane foam (PUF) insulation [15], 0,0199 for PEX-a pipes with polyurethane foam (PUF) insulation [16], and 0,04 for mineral wool slabs [17];

a_e – heat transfer coefficient from the outer surface of the thermal insulation, W/(m²·°C).

The ratio of the external diameter of the pipeline, including the thickness of the thermal insulation, to the external diameter of the pipe is defined as:

$$B = \frac{2 \cdot \delta_k}{D_{out}} + 1, \quad (3)$$

where δ_k – thickness of the thermal insulation layer, m;

D_{3tp} – external diameter of the pipe, m.

The calculations of heat losses for Alternatives 1, 2, and 3 are summarized in Tables 1 and 2.

A comparative diagram of heat losses during the heating period is presented in Fig. 1.

Table 1

Determination of Specific Heat Losses for Three Pipeline Alternatives in Heating Networks

Pipeline	D_{out} , m	δ_k , m	T_{avg} , °C	λ_k , W/(m·°C)	$\ln B$	r_{tot} , m·°C/W	q , W/m
Alternative 1							
T1	0,133	0,04	57,1	0,04	0,47	2,015	28,3
T2	0,133	0,04	49,9	0,04	0,47	2,015	22,3
Alternative 2							
T1	0,114	0,043	39,5	0,027	0,56	3,46	10,0
T2	0,114	0,043	32,2	0,027	0,56	3,46	7,9
Alternative 3							
T1	0,110	0,036	39,5	0,0199	0,5	4,173	8,3
T2	0,110	0,036	32,2	0,0199	0,5	4,173	6,5

Table 2

Determination of Heat Losses in the Heating Network Section from the Boiler House to the General Secondary School During the Heating Period (4 296 hours in accordance with [18])

Alternative	Length, m	Heat Losses, W	
		Hourly	During the Heating Period
1	59,6	3 619,8	15 550 654,1
2	59,6	1 276,1	5 482 000,2
3	59,6	1 057,6	4 543 321,3

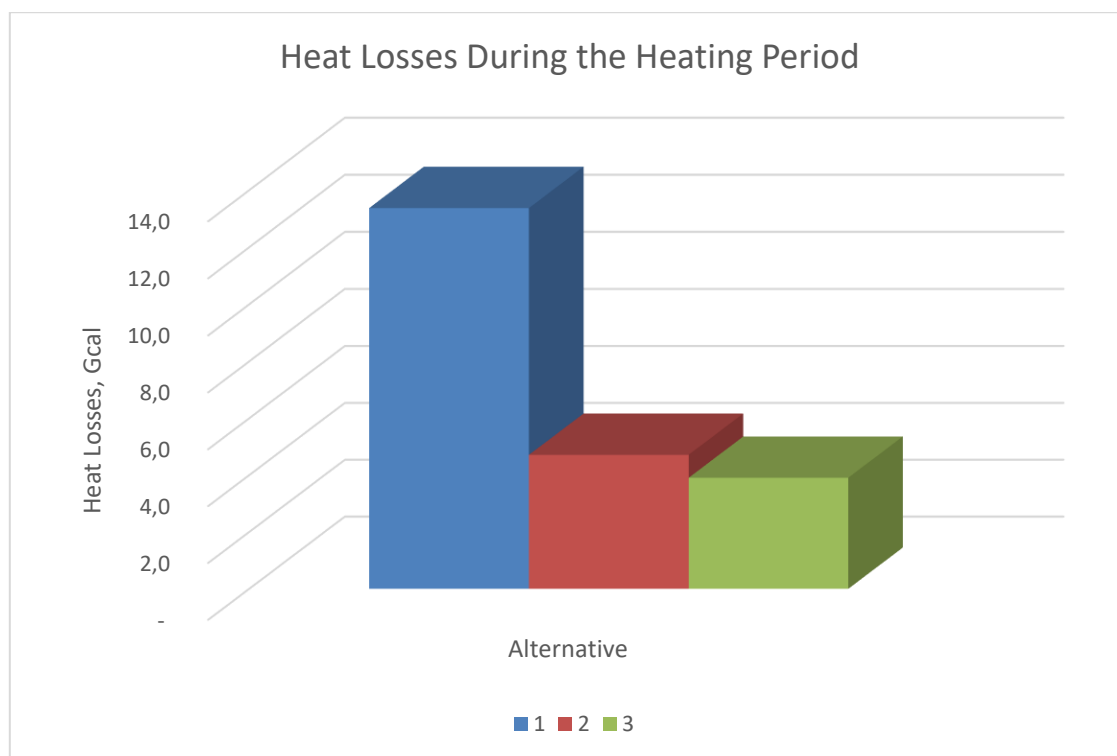


Fig. 1. Comparative Diagram of Heat Losses During the Heating Period

Comparison of Hydraulic Losses

According to data presented in [19], the heat carrier flow rate required for the heating systems of the general secondary school is determined as follows:

$$G_o = \frac{Q_o}{c \cdot \rho \cdot (T_1 - T_2)}, \quad (4)$$

where G_o – heat carrier flow rate for heating system demands, L/s;

Q_o – maximum thermal load of the heating system, kW;

c – specific heat capacity, J/(kg·°C);

T_1 – heat carrier temperature in the supply pipeline, °C;

T_2 – heat carrier temperature in the return pipeline, °C;

ρ – density of the heat carrier, t/m³.

The heat carrier velocity, m/s, is determined using the following equation:

$$w = \frac{4 \cdot G_o \cdot 10^3}{3,14 \cdot D_{in}^2}. \quad (5)$$

Hydraulic pressure losses in heating networks are determined by considering both linear and local losses using the Darcy–Weisbach equation:

$$R = \lambda \cdot \frac{L}{D_B} \cdot \frac{\rho' \cdot w^2}{2} + \Sigma \xi \frac{\rho' \cdot w^2}{2}, \quad (6)$$

where R – pressure losses, Pa/m;

λ – hydraulic resistance coefficient;

L – length of the section, m;

D_{in} – internal diameter of the pipeline, m;

ρ' – density of the heat carrier, kg/m³;

w – heat carrier velocity, m/s;

$\Sigma \xi$ – sum of local resistance coefficients.

The calculation of hydraulic losses for Alternatives 1, 2, and 3 is summarized in Table 3.

A comparative diagram of head losses is presented in Fig. 2.

Table 3

Hydraulic Loss Calculations for Alternatives 1, 2, and 3

Alternative	Q_o , kW	T_1 , °C	T_2 , °C	G_o , L/s	L , m	D_{in} , mm	w , m/s	R , Pa/m	ΔP , Pa	$\Sigma \Delta H$, mH ₂ O
1	255,9	95	70	2,54	59,6	125	0,21	7,3	564	0,12
2	255,9	55	40	4,18	59,6	106	0,47	30,9	2 386	0,5
3	255,9	55	40	4,18	59,6	90	0,66	57,6	3 879	0,81

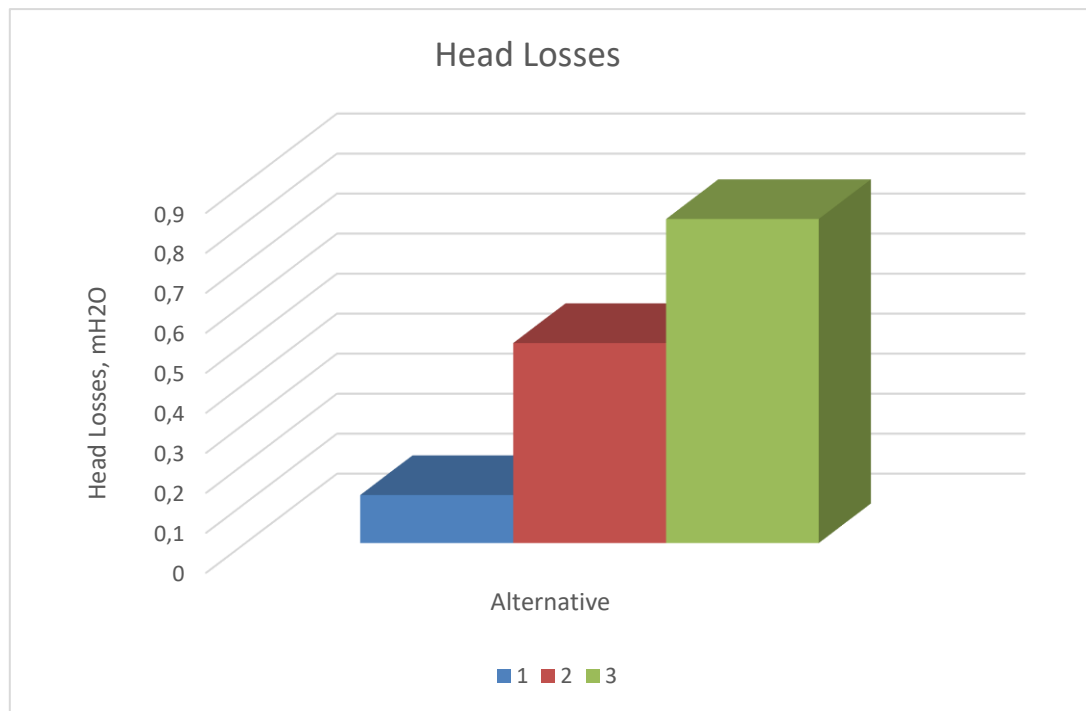


Fig. 2. Comparative Diagram of Hydraulic Losses

Comparison of Gas Consumption

The hourly gas consumption of the boiler house is determined using the following equation, m³:

$$B = \frac{Q_o \cdot 10^6}{Q_{LHV} \cdot \eta} \quad (7)$$

The gas consumption during the heating period is determined using the following equation, m³:

$$B_p = \frac{Q_o \cdot 10^6}{Q_{LHV} \cdot \eta} \cdot \frac{(t_i - t_{avg})}{(t_i - t_o)} \cdot T, \quad (8)$$

where Q_{LHV} – lower heating value of fuel, assumed as 8,000 kcal/m³;

η – boiler efficiency;

t_i – indoor air temperature, assumed as 20 °C;

t_{out} – average outdoor air temperature, assumed as -1 °C [18];

t_o – design outdoor air temperature for heating, assumed as -23 °C [18];

T – duration of the heating period, 179 days [18].

The calculation of boiler house gas consumption is presented in Table 4. The calculation of gas consumption required to compensate for heat losses in the heating network for Alternatives 1, 2, and 3 is presented in Table 5.

Comparative diagrams of boiler house gas consumption, gas consumption required to compensate for heat losses in the heating

network, and total gas consumption for Alternatives 1, 2, and 3 are presented in Fig. 3-5, respectively.

Table 4

Gas Consumption of the Boiler House Before and After Modernization

Alternative	Gas Consumption, m ³	
	Maximum Hourly	During the Heating Period
1	36,7	76 928,37
2	28,15	59 054,53
3	28,15	59 054,53

Table 5

Gas consumption for compensating heat losses in the heating network

Alternative	Gas Consumption, m ³	
	Maximum Hourly	Maximum Hourly
1	0,8	1 671,4
2	0,3	589,2
3	0,2	488,3

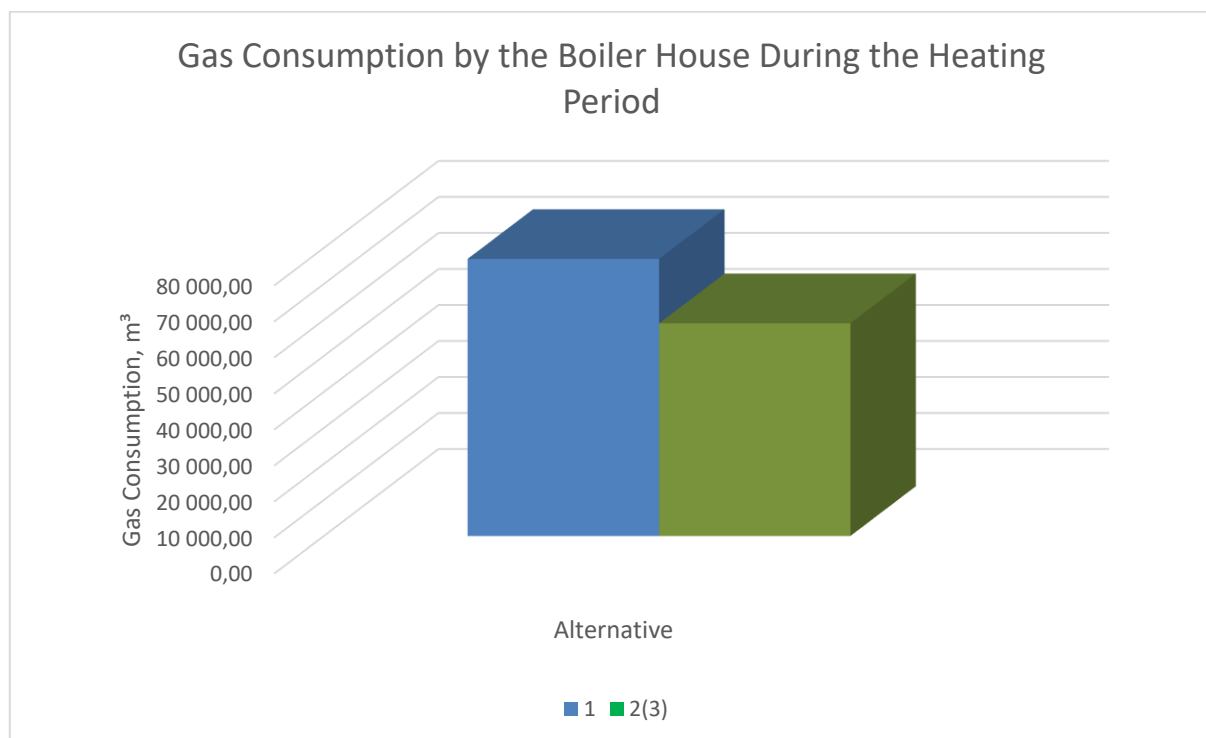


Fig. 3. Comparative Diagram of Boiler House Gas Consumption Before and After Modernization During the Heating Period

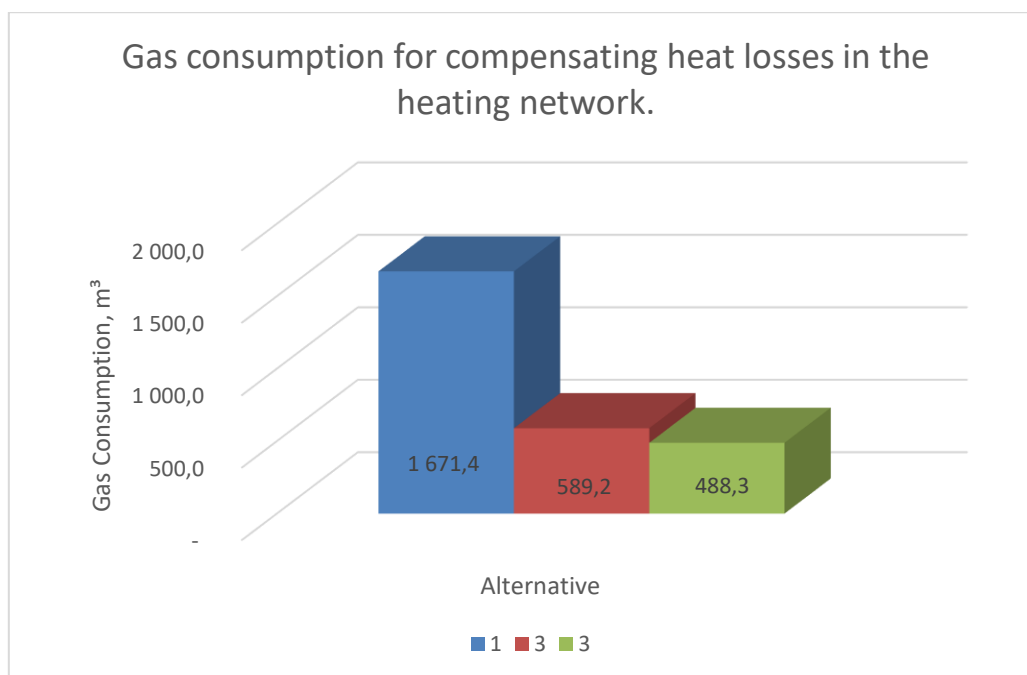


Fig. 4. Comparative diagram of gas consumption for compensating heat losses in the heating network during the heating period

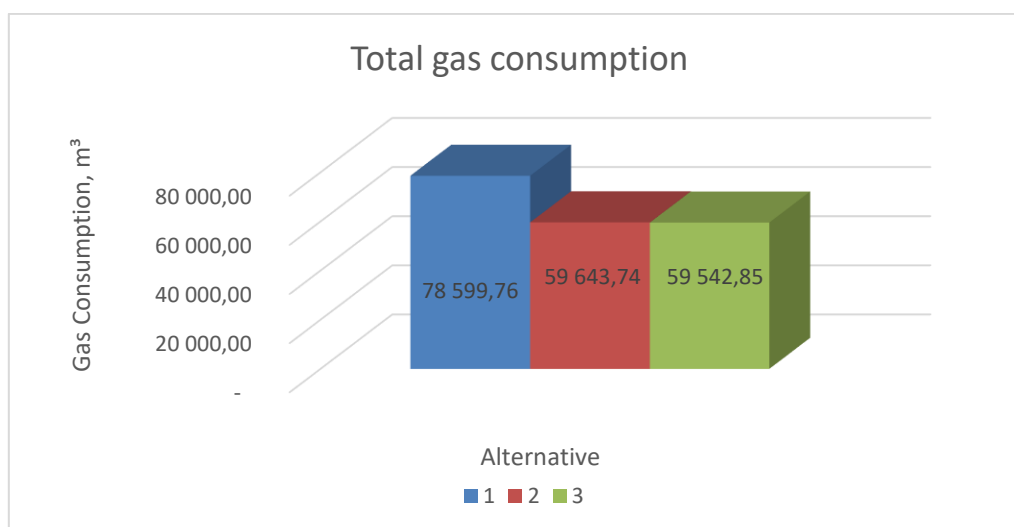


Fig. 5. Comparative diagram of total gas consumption during the heating period

Analysis of operating costs during the heating period in monetary terms

The main operating costs include the cost of natural gas and electricity. The cost of natural gas consists of the gas price and gas distribution service charges. For the calculations, the natural gas price was assumed

to be UAH 25,84 per 1 m³ according to the data provided in [20, 21].

The cost of electricity consists of the market electricity price, transmission tariff, and distribution tariff. For the calculations, the electricity price was assumed to be UAH 8,13 per 1 kWh according to the data provided in [22].

The amount of natural gas consumed during the heating period for the three options was determined previously and is as follows:

- Alternative 1 — 78 599,76 m³;
- Alternative 2 — 59 643,74 m³;
- Alternative 3 — 59 542,85 m³.

Electricity is consumed during the operation of the network pumps. The electricity consumption for pump operation is further determined for the three options. The network pumps are intended to overcome hydraulic losses, which include losses in the internal building heating system, hydraulic losses in the heating network, and losses in the boiler house. The sum of the internal building losses and the pressure losses in the boiler house is 5 m H₂O.

The pressure losses in the heating network are:

- Alternative 1 — 0,12 m H₂O;
- Alternative 2 — 0,5 m H₂O;
- Alternative 3 — 0,81 m H₂O.

In Alternative 1, a Wilo TOP-S 40/7 pump is installed. The electric motor power at the operating point, with a heat carrier flow rate of 9,14 m³/h and the required head of 5.12 m H₂O, is 0,34 kW.

In Alternative 2 and 3, an energy-efficient Wilo Stratos MAXO 50/0,5-9 pump with a frequency converter is installed. In Options 2 and 3, the heat carrier flow rate is 15,05 m³/h, while the total pressure losses are:

- Alternative 2 — 5,5 м вод. ст.;
- Alternative 3 — 5,81 м вод. ст.

The electric motor power at the operating point is 0,33 kW for Alternative 2 and 0,35 kW for Alternative 3. A comparative diagram of power consumption during the heating period is presented in Fig. 6.

The performance curve and technical characteristics of the Wilo TOP-S 40/7 pump for Alternative 1 are shown in Fig. 7. The performance curves and technical characteristics of the Wilo Stratos MAXO 50/0,5-9 pumps for Alternative 2 and 3 are shown in Figs. 8 and 9, respectively.

Fig. 10 presents a comparative diagram of operating costs in monetary terms during the heating period for the three options, taking into account the cost and distribution of natural gas, as well as the cost, transmission, and distribution of electrical energy.

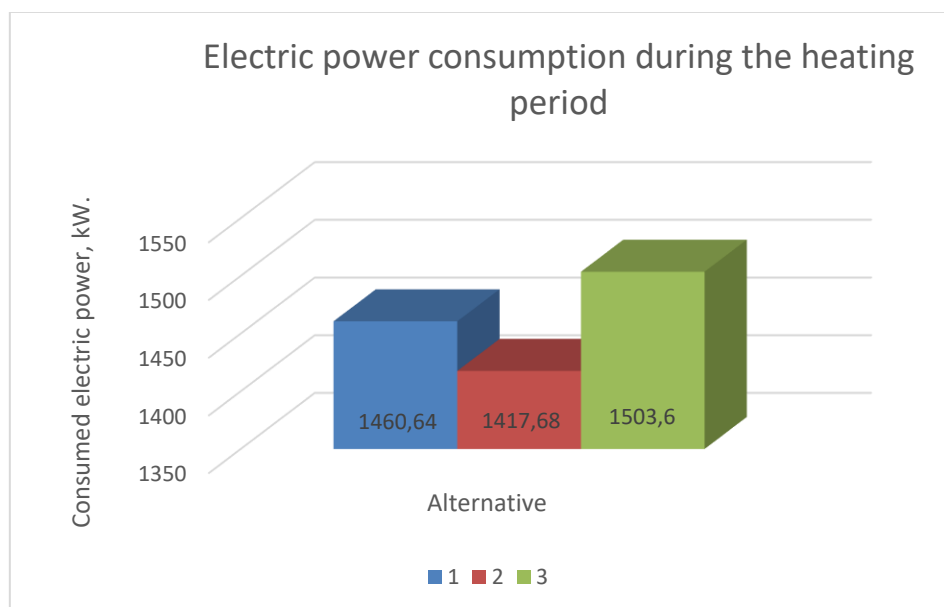
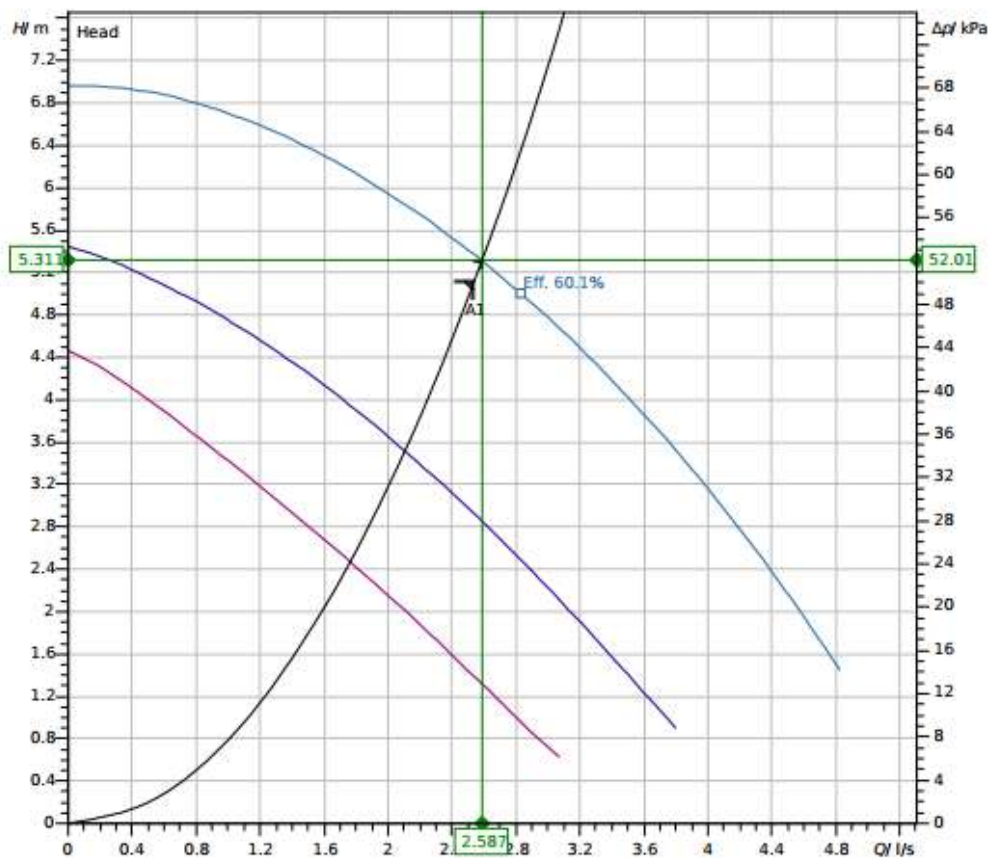


Fig. 6. Comparative diagram of electric power consumption during the heating period

TOP-S 40/7 (3~400/230 V, PN 6/10)

wilo

Pump curves



Fluid media	Water 100 %
Fluid temperature	20.00 °C
Requested flow	2.54 l/s
Delivery head (pressure unit)	5.12 m (50.14 kPa)
Delivered volume flow	2.59 l/s
Delivery head (pressure unit) at the duty point	5.31 m (52.01 kPa)
speed at duty point	2,600 1/min
Total electrical power consumption at the duty point	0.34 kW
Total shaft power at the duty point	0.23 kW
Hydraulic efficiency at duty point	59.77 %
Overall efficiency at the duty point	39.41 %

Fig. 7. Operating point and technical characteristics of the Wilo TOP-S 40/7 pump, Alternative 1 [14]

During the heating period, the cost savings achieved in Alternative 3 compared to

Alternative 1 amount to UAH 492 081,4 or 24,1 %.

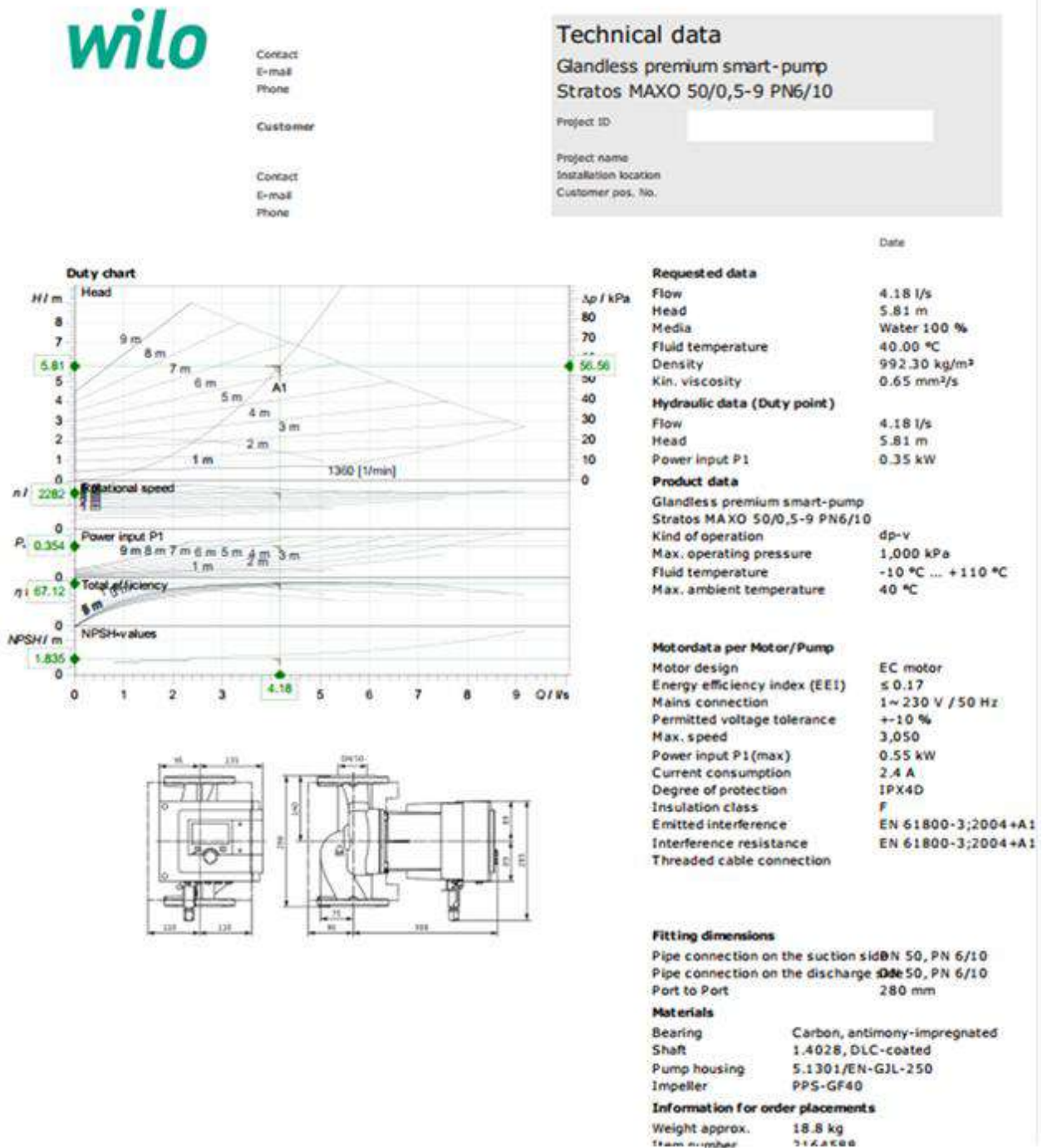


Fig. 9. Operating point and technical characteristics of the Wilo Stratos MAXO 50/0,5-9 pump, Alternative 3 [14]

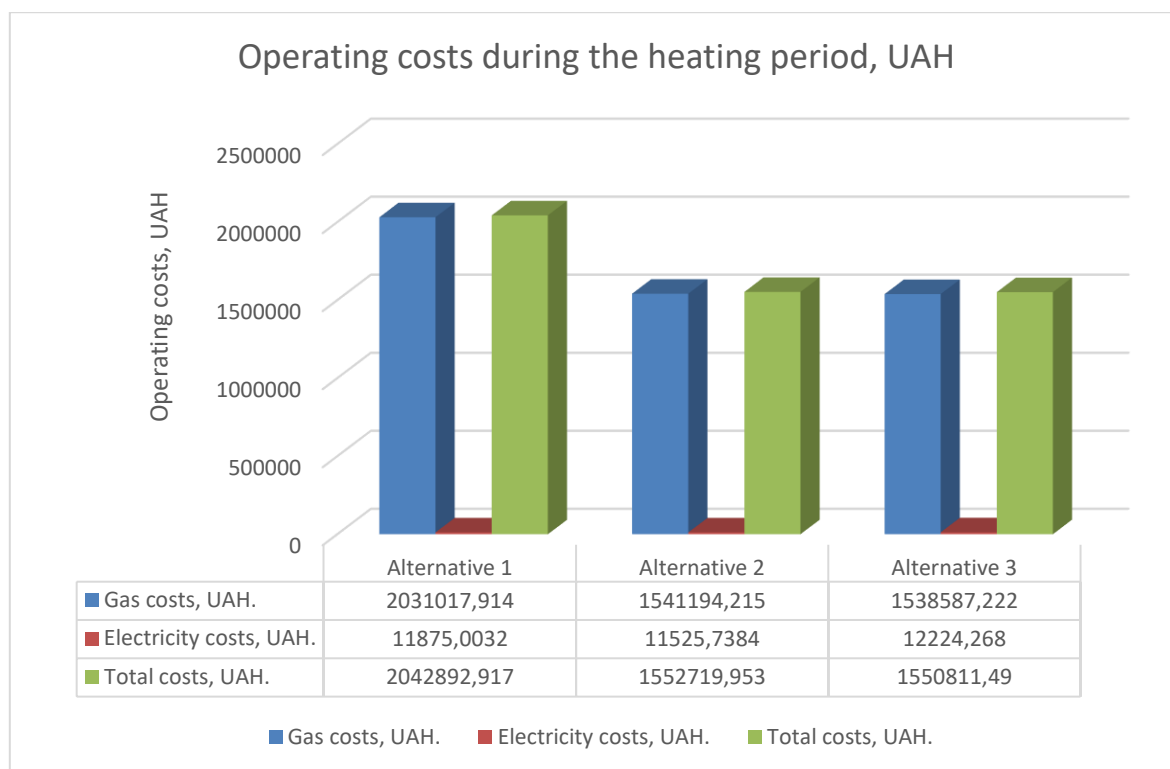


Fig. 10. Comparative diagram of operating costs in monetary terms during the heating period

Conclusions. A comparison of the options with temperature schedules of 95/70 °C and 55/40 °C makes it possible to conclude that the heat losses through the pipelines decreased by 64,75 % when comparing Options 1 and 2, and by 70,8 % when comparing Alternative 1 and 3.

However, it should be taken into account that Alternative 1 represents the existing heating network with oversized pipeline diameters and deteriorated thermal insulation (mineral wool slabs). Alternative 2 and 3 involve replacing the existing pipelines with new pre-insulated pipelines: steel pipelines in Alternative 2 and non-metallic pipelines in Alternative 3.

When comparing heat losses between Alternative 2 and 3, Alternative 3 is 17 % more efficient.

When the temperature difference is reduced, the heat carrier flow rate must be increased to ensure the design heat load. In comparing Alternative 1 with Alternative 2 and

3, the heat carrier flow rate increased by a factor of 1,646. However, due to the modernization of the boiler house equipment (replacement of the existing network pumps with energy-efficient pumps equipped with frequency converters), the increase in electric power consumption between Alternative 1 and 3 was insignificant, while in Alternative 2 it actually decreased.

In comparison with Alternative 1, electric power consumption during the heating period in Alternative 3 increased by only 2,9 %.

From a hydraulic point of view, Alternative 2 is the most efficient. However, it should be considered that Alternative 2 uses steel pipelines which, compared to non-metallic pipelines, are subject to internal corrosion and deposition buildup over time. This results in an increase in the roughness coefficient of the inner pipe wall surface and, consequently, an increase in hydraulic losses. Therefore, after a certain period of operation, the hydraulic losses in Alternative 2 will become higher than those in Alternative 3.

The replacement of old boilers with low efficiency by new condensing boilers made it possible to achieve energy savings of 23,2 %.

Alternative 3 is the most optimal solution, providing total savings of 24,1 % during the heating period compared to the existing system.

To enable a reduction in hydraulic losses in heating networks by decreasing the heat carrier flow rate, it is necessary to reduce the consumer heat load. This can be achieved through the thermal modernization of the

building, which is capable of improving energy efficiency by up to 45 % and, consequently, reducing the heat load.

It should also be noted that a promising direction for the development of district heating systems in Ukraine is the implementation of fourth- and fifth-generation technologies, which operate on the basis of low-temperature heating regimes and require comprehensive optimization of the thermotechnical and hydraulic characteristics of the system.

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Дата надходження статті: 03.07.2026 р.

Дата прийняття статті до друку: 14.09.2026 р.

Дата публікації (оприлюднення) статті: 16.10.2026 р.

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