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Efficiency of thermal energy consumption at industrial enterprises of Ukraine in conditions of environmental restrictions

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Abstract. The purpose of the study was to identify key patterns of thermal energy consumption and develop an analytical basis for optimising technological processes based on environmental requirements. The methodology involved a step-by-step calculation of the heat utilisation coefficient, specific consumption and heat loss structure based on instrumental data on heat consumption by the public joint-stock company Kamet-Steel for July-September 2024. The assessment of the efficiency of thermal energy consumption at the enterprise showed a stable, but insufficient level of energy use: the average coefficient was 81.0%, while heat loss did not decrease below 18.9%. Structural analysis showed that the largest share of losses was accounted for by pipelines (7.3%), heat exchangers (5.8%), cooling circuits (4.1%), and other losses (1.7%), which indicates the presence of several critical areas of inefficiency. Specific heat consumption per unit of production ranged from 0.1815-0.1923 Gcal/t and increased in September, despite a decrease in production volumes, which indicates the inertia of the supply system. Based on the results, a technical and analytical basis was formed for the reconstruction of energy-efficient infrastructure elements with an estimated potential to reduce losses by 6-8%. The presented conclusions also confirmed the feasibility of digital monitoring as a tool for stabilising costs and increasing adaptability to changes in the production load. The results obtained can be used for the development of technical and economic measures for the reconstruction of heat transport infrastructure of industrial enterprises, in particular, through the optimisation of heat exchange modes, modernisation of pipelines, and the introduction of residual heat recovery systems. This will reduce specific energy costs, stabilise the heat balance, and reduce the environmental burden

Keywords: heat efficiency; metallurgical production; carbon; pipeline networks; cooling circuits; recuperation

Introduction

Industrial enterprises of Ukraine, in particular in the metallurgy sector, are increasingly operating under stricter environmental regulations and growing energy efficiency requirements. In heat supply systems that serve high-temperature technological processes, a significant part of energy is lost due to worn-out infrastructure, inconsistency of heat flows with the dynamics of production, and the lack of recovery mechanisms. Specific losses are caused by the inertia of heat engineering systems, instability of heat exchange, and low accuracy of circuit control. In such conditions, thermal energy consumption becomes a factor that affects not only the production cost, but also the overall environmental footprint of the enterprise. This justifies the need to implement technological solutions aimed at structural modernisation of heat supply systems and increasing their adaptability to changes in production load.

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Among the research in the field of industrial energy efficiency, the study by M. Farghali *et al.* (2023) proposed a comparative systematisation of energy saving strategies based on examples from different countries in the context of the energy crisis. This was a generalisation of current approaches to integrating renewable sources and load optimisation. However, heat consumption as a separate technical component was not considered. The study by C.-L. Miao *et al.* (2020) analysed the relationship between energy consumption, environmental pollution and innovative efficiency on the example of Chinese industry, but without considering heat losses in technological processes. On the other hand, L. Dai & M. Wang (2020) developed a model for assessing the impact of carbon constraints on the economic performance of thermal generation, focusing on the macro level without detailing the structure of industrial heat consumption.

An important contribution to the development of the modern discourse on energy efficiency in Ukraine was made by V. Derii *et al.* (2023b), who analysed the impact of structural changes in the district heating system on greenhouse gas emissions and substantiated the need for technical reconstruction of the heat and power infrastructure. This study proved that the transformation of thermal circuits towards decentralisation, modernisation of equipment, and introduction of cogeneration technologies can significantly reduce the carbon footprint of the energy system, although without direct detailing of heat losses in the industrial sector. The study by V.P. Babak *et al.* (2023) for the first time systematised technical and economic approaches to improving energy efficiency in industry at the level of a national monograph, including the analysis of reserves for reducing heat losses, but these solutions remain conceptual and require empirical verification in real production conditions. The paper by U. Andrusiv *et al.* (2023) was distinguished by its originality due to the use of a simulation model to assess the efficiency of using fuel and energy resources, considering the country's energy balance. However, the study focused on the macro level and did not cover structural analysis of thermal energy losses in production systems, which limits its application value for industrial enterprises. Actual aspects of forecasting the needs for thermal energy in the conditions of martial law and post-war reconstruction were considered by O. Maliarenko *et al.* (2025), who presented a scenario approach to estimating heat load in the future until 2030. The models proposed by the researchers considered socio-economic transformations and infrastructure losses, which created an analytical basis for substantiating the needs for modernisation of industrial heat supply systems.

Comprehensive reports National Academy of Sciences of Ukraine Institute of General Energy (2024) and National Academy of Sciences of Ukraine Institute of general energy (2025) provided a generalised review of scientific and organisational activities in the field of energy efficiency improvement, in particular, they noted the potential for residual heat utilisation, modernisation of thermal power plants (TPPs) and the introduction of innovative energy saving systems in industry. These documents formed a conceptual basis for substantiating the need for reconstruction of energy systems, but contained mainly strategic approaches without empirical detailing of heat consumption processes. The study by M.M. Kulyk & O.V. Zgurovets (2020) investigated the effect of derivatives from regulatory capacities on frequency stability in power systems with wind power plants (WPPs), proposing a mechanistic model relevant for estimating load dynamics, but without considering thermal processes in production. Instead, the study by M. Andersen & J. Noailly (2022) modelled the technological development of the coal industry, considering environmental constraints, which allowed predicting adaptation scenarios for the sector, although without directly focusing on the loss of thermal energy. Despite the availability of strategic and conceptual developments, as of 2025, studies have not provided a reasonable empirical assessment of the efficiency of thermal energy consumption in the real functioning of industrial enterprises.

The purpose of this study was to quantify the parameters of thermal energy consumption in the industrial sector of Ukraine, considering technological losses and environmental restrictions. Within the framework of the set goal, the study included an analysis of the structure of heat energy use at enterprises, identification of key sources of losses in technological nodes, and determination of areas for improving energy efficiency in the context of increased environmental regulation.

Materials and Methods

The study was conducted at the metallurgical enterprise Public Joint Stock Company (PJSC) Kamet-steel (Kamyanske, Dnipropetrovsk Oblast, Ukraine) in the period from July 1 to September 30, 2024. This enterprise was chosen as a representative unit of heavy industry in Ukraine with a full metallurgical cycle, centralised generation and utilisation of thermal energy. The selected period corresponded to a stable summer production regime, which excluded the influence of seasonal fluctuations and planned equipment shutdowns, ensuring representativeness of thermal performance indicators.

Indicators were collected automatically through the industrial monitoring system Supervisory Control and Data Acquisition (SCADA) with data recording every 15 minutes. For analytical calculations, the average values for each technological change were used (00:00-08:00, 08:00-16:00, 16:00-00:00), with subsequent aggregation to average daily, weekly, and monthly intervals. For each of the parameters, average values were calculated both in terms of time and volume of output. In the course of the study, the following thermal performance indicators were automatically recorded: the volume of heat energy consumed (Gcal/day), specific heat consumption per unit of production (Gcal/t of steel), heat losses at different stages of the technological cycle (%), the temperature and pressure of the heat carrier at the inlet and outlet of heat exchangers, the duration of heat transfer (h), the volume of recycled secondary heat (Gcal/day), the temperature of cooled flows. The amount of useful heat used was determined on the basis of consumption indicators in the main heat technology units, in particular, in blast furnace and steelmaking units. The measurements were carried out by the company's standard accounting system using Proline Prosonic Flow 93T ultrasonic flow meters (Endress+Hauser, Germany), Pt100 temperature sensors (Siemens, Germany) and VEGABAR 82 pressure sensors (VEGA Grieshaber KG, Germany). The instruments were calibrated in accordance with the company's internal regulations in compliance with the requirements of DSTU ISO 10012:2005 (2005) for measurement control systems.

To calculate the efficiency of thermal energy consumption, the heat useful life coefficient (*KKWT*) was used, which was determined by the equation 1:

$$KKWT = \frac{Q_{useful}}{Q_{total}} \times 100\%, \tag{1}$$

where Q_{useful} – amount of heat used directly in the process (Gcal); Q_{total} – total amount of heat supplied to the system (Gcal).

To reflect the inefficient use of thermal energy, the level of heat losses (*W*) was additionally calculated using the equation 2:

$$W = \frac{Q_{total} - Q_{useful}}{Q_{total}} \times 100\%. \tag{2}$$

This indicator allows quantifying the proportion of heat that is lost during transportation or use. Losses were determined based on the balance method with a comparison of the supplied and useful heat, considering heat losses in pipelines, heat exchangers, and cooling circuits.

The specific heat consumption for the production of one tonne of steel was estimated using the equation 3:

$$q = \frac{Q_{total}}{P}, \tag{3}$$

where q – specific heat consumption (Gcal/t); P – total output (t).

All these equations were developed based on generally accepted methods for calculating energy efficiency in industrial heat and power engineering (Barakhta & Krazhan, 2008).

Production information was collected within the framework of the current regulations of PJSC Kamet-Steel in coordination with responsible specialists. The data used in the analytical calculations did not contain any commercial secrets and were generalised to a level that excludes the disclosure of technologically sensitive characteristics. All measurement procedures were carried out remotely and did not affect production processes, without creating risks to the environment, equipment or personnel. There was no interference with the operation of technological systems during the study.

Results and Discussion

General indicators of thermal energy consumption in the production cycle. As part of the analysis of thermal energy consumption at the enterprise of PJSC Kamet-Steel, special attention was paid to the dynamics of average weekly values, which allowed tracing the relationship between fluctuations in technological activity, in particular, changes in steel output volumes and the daily thermal load (Table 1). This approach provided a representative basis for further interpretation of energy consumption levels in the context of the technical condition of heat supply systems and the efficiency of the enterprise's heat balance.

Table 1. Average weekly heat consumption and steel output per day at PJSC Kamet-Steel in July-September 2024

Week	Average heat consumption, Gcal/day	Average daily steel output, t	Total weekly steel output, t
01-07.07	975.3	5,240	36,680
08-14.07	980.7	5,310	37,170
15-21.07	987.5	5,190	36,330
22-28.07	990.1	5,350	37,450
29.07-04.08	987.2	5,420	37,940
05-11.08	998.4	5,500	38,500
12-18.08	1,002.3	5,480	38,360
19-25.08	1,005.8	5,470	38,290
26.08-01.09	999.4	5,320	37,240
02-08.09	973.1	5,200	36,400
09-15.09	977.6	5,140	35,980
16-22.09	970.8	5,080	35,560
23-30.09	980.9	5,100	40,800 (8 days)

Source: compiled by the author

Aggregated data show that the average weekly heat consumption ranged from 970.8 to 1,005.8 Gcal/day, with the maximum load recorded in August. The increase in heat consumption during July – mid-August correlated with an increase in production volumes-from 36,330 to 38,500 tonnes of steel per week. The highest average weekly intensity of energy consumption was recorded in the period August 05-11, when the heat load reached 1,005.8 Gcal/day with the output of 38,500 tonnes. This dynamic confirmed the link between the production schedule and heat load. But in September, starting from the second week, there was a gradual decrease in heat consumption – from 984.2 to 970.8 Gcal/day, which was accompanied by a corresponding decrease in output volumes – from 36,400 to 35,560 tonnes per week. This decline reflects the impact of technical routine shutdowns of individual units and a decrease in the load of melting capacities due to preparations for the autumn repair period. Such a change in the intensity of heat consumption indicates the need for adaptive control of heat flows depending on production activity.

The results obtained confirmed the data of V. Derii *et al.* (2023a), who noted that the high inertia of heat engineering systems and the insignificant reaction of the heat supply system to fluctuations in production volumes are characteristic of Ukrainian metallurgical enterprises. According to their estimates, typical values of heat consumption under constant load conditions are 930-1,020 Gcal/day, which is fully consistent with the results obtained in this study. However, the results of Polish enterprises, described in the paper by R. Wolniak *et al.* (2020), showed significantly lower daily heat consumption with a similar volume of steel output – 850-880 Gcal/day, which is 10-12% less than the Ukrainian values. This is conditioned by the high degree of digitalisation of energy management systems, the integration of Industry 4.0 technologies, and the active introduction of recovery systems. This comparison allows to conclude that there is a potential for optimising heat consumption at PJSC Kamet-Steel through the modernisation of heat distribution systems. The study by K. Widera *et al.* (2024) emphasised that the stability of energy consumption at variable production intensity is a sign of weak adaptability of systems. A similar trend was recorded in the current study – the heat load in September remained stable, despite a decrease in production volumes by more than 2,000 tonnes per week, which indicates the existence of a baseline level of losses. In this paper, the researchers proved that under such conditions, enterprises can lose up to 5-6% of their potential energy efficiency.

Data on the average monthly heat consumption allowed summarising and demonstrating the dynamics of changes in energy loads during the observation period. Indicators for each month provided an opportunity to assess the impact of production activity on total heat consumption, identify periods of increased or reduced load, and confirmed the dependence of thermal dynamics on changes in the production schedule (Fig. 1).

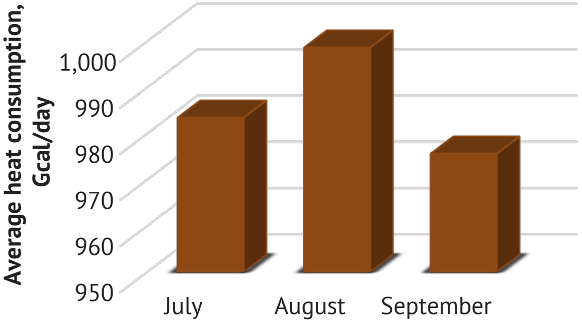

Figure 1. Average monthly heat consumption at PJSC Kamet-steel

Source: compiled by the author

The graphical interpretation of the average monthly heat consumption indicators showed a clear dependence of the heat load on production activity. The increase in values in August corresponds to the peak load phase of the metallurgical cycle, due to the continuous operation of the main units without technological stops. In September, there was a gradual decrease in heat consumption, which correlates with a decrease in output and preparation for routine maintenance. The inertia of thermal processes causes a stable level of basic losses, which cannot be adjusted quickly, even in conditions of reducing production volumes. This indicates the limited flexibility of the existing infrastructure to changes in the production schedule.

According to the observations of T. Sengyu & V. Khare (2023), the low dynamic sensitivity of heat consumption systems in response to changes in output volumes is a typical limitation for enterprises that do not have integrated automated heat exchange management systems. In this study, this was also reflected in a slight decrease in daily costs with a reduction in steel output in September, which indicates the presence of structural inertia. From the standpoint of environmental efficiency, such losses without direct reference to the production result form an unproductive heat load on the environment, in particular, due to excessive CO_2 emissions in cases where the source is organic fuel. H. Na *et al.* (2021) noted that in order to achieve environmental neutrality, enterprises should implement energy-efficient control models that minimise unjustified heat costs by 10-15%. The results obtained confirmed the high dependence of heat consumption on the technological load, while at the same time identifying a constant level of maladaptive losses that form an excessive load on the energy balance of the enterprise. This situation indicates the need for targeted optimisation of the structure of heat consumption, considering the localisation of losses and increasing the efficiency of residual heat utilisation.

Evaluation of the efficiency of using thermal energy. Evaluation of the efficiency of heat consumption at the selected enterprise was carried out by calculating the coefficient of useful use of heat, reflecting the share of heat energy that was directly used in the technological process. Simultaneously, the level of heat loss was used for quantitative assessment of losses, which allows determining the share of unused heat from the total amount of energy supplied. Both indicators were calculated according to equations (1) and (2) (Table 2).

Table 2. Results of calculation of KKWT and heat energy losses at weekly intervals

Week	Q_{total} (Gcal/day)	Q_{useful} (Gcal/day)	*KKWT* (%)	Heat loss *W* (%)
01-07.07	975.3	782.4	80.2	19.8
08-14.07	980.7	794.3	81.0	19.0
15-21.07	987.5	801.9	81.2	18.8
22-28.07	990.1	808.7	81.7	18.3
29.07-04.08	987.2	800.1	81.1	18.9
05-11.08	998.4	812.9	81.4	18.6
12-18.08	1,002.3	816.8	81.5	18.5
19-25.08	1,005.8	818.2	81.4	18.6
26.08-01.09	999.4	809.1	81.0	19.0
02-08.09	973.1	788.9	81.0	19.0
09-15.09	977.6	790.1	80.8	19.2
16-22.09	970.8	782.0	80.5	19.5
23-30.09	980.9	788.6	80.4	19.6

Source: compiled by the author

The data show that *KKWT* ranged from 80.2 to 81.7%, indicating a moderate but stable level of thermal efficiency. The highest figure – 81.7% – was reached during the week of July 22-28, which indicates an improvement in the heat balance in conditions of stable production load. Simultaneously, the lowest value – 80.2% – was recorded in the first week of July, when the system probably has not yet entered optimal operation after the off-season regulations. The rate of heat loss, respectively, ranged from 18.3% to 19.8%, and in none of the weeks the loss was reduced to a limit below 18%. This indicates the presence of constant systemic losses of thermal energy in the enterprise's infrastructure, mainly associated with pipeline networks, cooling systems, and inefficient utilisation of residual heat.

A detailed analysis showed that the change in *KKWT* was most influenced by: the condition of heat exchangers, load stability in blast furnace and steelmaking units, and the secondary heat recovery coefficient. For example, the increase in *KKWT* in the second half of July was associated with minimising shutdowns and improved coordination between heat carriers and production volumes. Despite the achievement of *KKWT* at the level of 80.2-81.7% during the analysed period, the available reserve for improving efficiency was at least 3-5%, this optimisation potential was conditioned by excessive heat losses in pipelines, insufficient level of residual heat recovery, and limited adaptability of heat supply to load changes. Promising measures are the introduction of automated heat flow management systems, reconstruction of heat exchange equipment, and integration of local recycling systems at the level of technological units, which will increase the *KKWT* to a normatively justified level. Comparison with similar results in other studies confirmed the general trend of maintaining heat engineering inefficiency in metallurgical production. According to M. Xu & B. Lin (2022), the average level of heat efficiency at metallurgical enterprises in China is 78-83%, which is almost identical to the values obtained in the study (80.2-81.7%). The researchers emphasised that the main limiting factor of efficiency is the inertia of heat supply systems – their inability to flexibly respond to fluctuations in production loads. This was also observed at PJSC Kamet-Steel, where the increase in load in August was not accompanied by a proportional decrease in heat loss. Similar conclusions were presented in the paper by Z. Su *et al.* (2021), who noted that the lack of technologies for multi-level utilisation of residual heat can lead to losses of more than 20%. In the current study, losses were 18.9%, which indicated partial compensation, but confirmed a structural shortage of recycling mechanisms, especially in cooling circuits and the pipeline network.

S. Zhang *et al.* (2022) reported that the introduction of industrial-type thermal accumulators can reduce heat losses by 3-4%, which is comparable to the identified optimisation potential at the enterprise. Since no traces of the use of storage technologies were recorded in the course of the study, such modernisation was considered as one of the least resource-intensive steps to increase the *KKWT*. From the standpoint of environmental efficiency, the results of the study are consistent with the provisions of S.R. Paramati *et al.* (2022), who stated that each percentage reduction in heat loss correlates with a reduction in CO_2 emissions, especially in systems with heavy use of fossil fuels. Given that PJSC Kamet-Steel operates in a carbon-intensive production environment, the current loss rate of almost 19% means that the excess carbon footprint is likely to remain, which requires a separate assessment. A. Arifjanov *et al.* (2020) investigated the effectiveness of technical reconstruction of pipeline infrastructure, in particular, due to changes in the geometric parameters of pipes and the introduction of new insulation materials. According to the researchers, losses can be reduced to 5-6% at critical points, which in the conditions of Kamet-Steel potentially reduces the overall W indicator from 18.9% to 13-14% without radical changes in production logistics. Thus, the detected thermal imbalance with the share of unused energy of more than 18% indicated systemic structural shortcomings in the management of heat flows, the elimination of which will provide regulatory limits of efficiency along with a comprehensive increase in energy and environmental efficiency of production, in particular, through increasing the flexibility of heat supply systems, integration of heat accumulators, and reconstruction of backbone networks.

Structure of heat losses and their technological localisation. The design of industrial thermal engineering systems is such that a significant portion of the energy supplied does not reach the target technological nodes, due to both design features and infrastructure wear and tear. To identify the sources of system losses at the PJSC Kamet-Steel, the heat balance was decomposed into the main components: losses in pipelines, heat exchange equipment, cooling circuits, and other infrastructure losses. Calculations were carried out based on indicative relations between the supplied energy (Q_{total}) and the volumes of heat recorded at the end-use points (Q_{useful}), followed by the distribution of losses by individual technological links.

The weighted average level of heat energy losses at the enterprise during July–September 2024 was 18.9%. The distribution of heat losses between the main infrastructure elements allowed to identify critical areas of energy efficiency and form priorities for technical intervention. To visualise the contribution of each structural component to the overall loss rate, a graph was constructed showing the specific proportion of losses in pipelines, heat exchangers, cooling systems, and non-localised zones (Fig. 2).

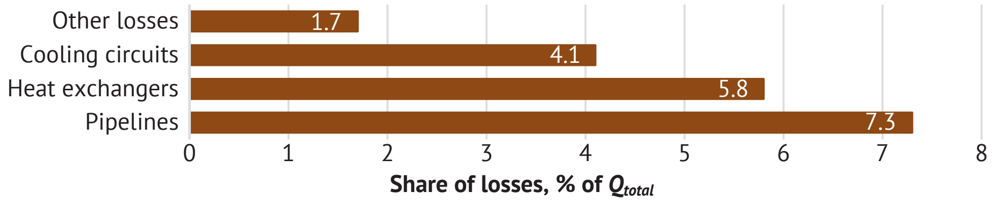

Figure 2. Distribution of heat losses by infrastructure components

Source: compiled by the author

Structural analysis of heat energy losses confirmed that the largest share is accounted for by main pipelines – 7.3% of the total volume of heat energy supplied (Q_{total}), which indicates the determining contribution of this component to the systemic inefficiency of the heat transport infrastructure. This result is explained by physical wear of the insulation, insufficient sealing of joints, and failure to comply with technical regulations, which makes it impossible to effectively compensate for losses without network reconstruction. In second place in terms of losses is heat exchange equipment (5.8%), where losses were caused by violation of heat transfer modes, low flow turbulence, and outdated design. In cooling circuits, losses were 4.1% and were mainly associated with inefficient utilisation of residual heat, in particular, due to excessive water cooling without reverse heat recovery mechanisms. The category "other losses" covers 1.7% and included losses in shut-off valves, strapping, drains, and other small system elements. Their localisation is more complex, but they can be compensated by point-based technical interventions at minimal cost.

The overall picture indicates a disparity in the loss structure, where a significant share was occupied by components that can theoretically be effectively upgraded. This creates prerequisites for the development of a phased thermal rehabilitation strategy, which should cover the priority renewal of pipelines and heat exchangers, and the development of a feasibility study for the recovery of lost heat from cooling circuits. Comparison with the results of the study by D. Al Momani *et al.* (2023) showed that the level of losses in pipeline systems of industrial enterprises in the food sector in the absence of modernisation was 6-9%. The indicator of 7.3% obtained at PJSC Kamet-Steel is comparable under conditions of similar thermal load scales, although at higher temperatures of the technological cycle. The applied approach of local thermal audit was consistent with the methodological approaches set out in the mentioned source.

According to the generalised conclusions of M. Meng & D. Qu (2022), the share of losses in heat transportation and utilisation systems in some regions of China is up to 20%, and energy efficiency in general ranges from 76-85%. The loss structure recorded at the enterprise under study reproduced a similar configuration, where the predominant share was accounted for by pipeline infrastructure and heat exchangers. Fixing a stable loss rate of almost 19% indicated an additional thermal load, which, according to the model by C. Tang *et al.* (2025), has a direct relationship with the growth of carbon production intensity. This suggests that even in the absence of direct monitoring of CO_2 emissions, such thermal inefficiency can be an indirect indicator of increased impact on the climate system. In this context, the integration of environmental indicators into the energy audit system is not only desirable, but also a methodologically justified condition for modern energy environmental management. As part of the study by G. Kaletnik *et al.* (2020), the importance of residual heat utilisation as one of the key elements for achieving energy autonomy of industrial facilities was emphasised. The recorded level of losses in the enterprise's cooling systems (4.1%) confirmed the feasibility of creating heat recovery systems, even in medium-temperature conditions.

A comparative analysis of the obtained heat loss indicators with the results of previous studies revealed both elements of consistency and structural discrepancies due to the specifics of the research object. In particular, according to V.V. Dubrovsky & A.A. Shraiber (2020), heat losses in cooling systems based on film heat exchange can reach 4-5% of the total energy balance due to inefficient open-circuit heat transfer and significant influence of meteorological factors. In the conditions of Kamet-Steel, losses in circulation cooling systems were commensurate – at the level of 4.1%, which confirmed the stability of the scale of losses under the condition of a similar cooling principle (cooling towers and open water circuits), but under more controlled production conditions. The results obtained by O.A. Shraiber & V.B. Redkin (2018) indicate that in the case of insufficient turbulence in heat exchangers, the heat transfer efficiency decreases, which lead to losses of up to 6-7% of the supplied heat. In the course of this study, the average level of losses in heat exchangers was 5.8%, but in some periods – in particular, in August – local peaks were recorded that exceeded 6.1%. This behaviour is associated with an increased production load and deterioration of hydrodynamic conditions in heat exchange modules, which is consistent with the authors' hypotheses and indicated the presence of a maladaptive mode of operation of equipment at peak loads.

These values indicated that there is a potential to increase efficiency by at least 6-8% due to the modernisation of pipeline insulation and reconstruction of heat exchange equipment. In particular, the use of a new generation of plate heat exchangers reduced specific losses by 2-3%, and the introduction of multi-layer insulation with microporous fillers – by another 4%. In addition, correction of cooling modes through the introduction of reverse temperature control in circulation loops can reduce losses in cooling towers and heat carriers. The results of loss localisation confirmed the multicomponent nature of the inefficiency of the heat supply system, where each structural element makes a significant contribution to the total energy losses. Given the relative constancy of losses, it can be argued that there is infrastructure inertia, which prevents a proportional reduction in energy consumption during periods of reduced production. This justifies the need for a detailed energy audit using thermography, hydraulic modelling, and feasibility studies of reconstruction solutions.

Specific heat consumption per unit of production and influencing factors. Energy efficiency assessment at the level of individual product units is necessary for understanding the real level of technological optimisation of the enterprise. As part of the study, the company calculated the specific heat consumption (*q*), which reflects the average amount of heat used in GCal for each tonne of steel produced. The calculation was performed using the equation (3) (Table 3).

Table 3. Specific heat consumption per unit of steel produced at PJSC Kamet-Steel

Week	Specific heat consumption (Gcal/t)
01-07.07	0.1861
08-14.07	0.1847
15-21.07	0.1903
22-28.07	0.1851
29.07-04.08	0.1822
05-11.08	0.1815
12-18.08	0.1829
19-25.08	0.1839
26.08-01.09	0.1878
02-08.09	0.1871
09-15.09	0.1901
16-22.09	0.1911
23-30.09	0.1923

Source: compiled by the author

Fluctuations in specific heat consumption per unit of production in the analysed period ranged from 0.182 to 0.192 Gcal/t, which reflects the uneven adaptation of the heat engineering infrastructure to changes in the production load. There is a clear trend: during periods of high technological activity (in particular, in August), the system shows increased consistency between energy supply and production volumes, which reduces unit costs. But in the conditions of a gradual decrease in production volumes in September, the heat load per unit of production increased, which indicated structural inertia and the presence of basic losses that cannot be adjusted in real time.

Such dynamics are inherent in enterprises with a complex branched heating network, where thermal energy is supplied not in proportion to real demand, but along inertial circuits that react with a time lag. This behaviour of the system may be conditioned by the lack of automated means of monitoring heat flows, low accuracy of temperature control, and technical losses in the network. This indicated the need to integrate elements of flexible energy management, especially in the phases of declining production. According to the findings of T. Jiang *et al.* (2022), in sectors with a high specific heat load, there is a direct relationship between the maladaptivity of thermal power systems and carbon intensity. It was found that a steady increase in unit costs at the end of the study period not only indicates a deterioration in energy efficiency, but also has environmental consequences that require further study in the context of the industrial decarbonisation strategy.

The problem of irrational heat distribution in low-load phases was also mentioned in the study by Z. Chen *et al.* (2023), where it was proved that low controllability of heat exchange processes under conditions of variable circulation modes leads to local energy imbalances. The company's observed increase in q in September with a decrease in steel output is fully consistent with this observation. The researchers also emphasised that even minor improvements in the field of thermal insulation or circuit automation can significantly reduce unit costs. These results are supported by S. Gennitsaris *et al.* (2023), who showed that the integration of digital unit cost monitoring systems in real time allows quickly identifying inefficient production modes and reducing q by 3-5% without the need to attract significant investment. In this context, the lack of dynamic control over heat flows at the Kamet-Steel enterprise can be a determining factor for consistently high losses during periods of reduced load.

At the strategic level, the results of the study by M. Zos-Kior *et al.* (2021) indicated that the specific energy consumption indicator should be an integrated element of a multi-level resource efficiency assessment system, since it reflects the quality of energy management throughout the entire product life cycle. The dynamics of the q-indicator established in the course of this study confirms the feasibility of localised loss control and the introduction of technological modifications focused not only on the economic, but also on the environmental performance of energy consumption. The results obtained are consistent with international trends and empirical estimates from other industries, indicating the need to implement technical and economic solutions to improve efficiency. The dynamics of specific heat consumption demonstrated their sensitivity to changes in the production load and the feasibility of using this indicator as a diagnostic tool for optimising heat supply. The implementation of system improvements would allow for a gradual increase in energy efficiency, considering complex technical and environmental parameters.

Environmental consequences of heat losses and prospects for decarbonisation of industrial energy consumption. Heat losses in industrial power systems are not only of technical, but also of environmental significance. The loss of almost a fifth of the heat indicated the existence of a constant thermal load on the system, which not only reduces energy efficiency, but also indirectly generates an increase in greenhouse gas emissions. In technologically complex industries, such as metallurgy, where the bulk of energy is supplied in the form of heat, the degree of efficiency of its use directly determines the intensity of the carbon footprint of the finished product. The loss structure is dominated by pipelines, heat exchangers, and cooling circuits. The decline in efficiency at these stages indicated not only the technical obsolescence of infrastructure elements, but also the lack of effective heat recovery mechanisms, which are already standard practice in a number of countries. For example, the absence of heat accumulators or the secondary use of residual heat in cooling systems does not reduce peak losses, which is especially pronounced during periods of reduced production load. Heat losses are not a constant technological value, but act as an indicator of the system's adaptability to production dynamics. Their growth against the background of a decrease in output volumes in September indicates infrastructure inertia and a low degree of integration of intelligent control systems.

Comparison with the results of the study by T. Jiang *et al.* (2022) confirmed that in sectors with a high specific heat load, such as energy and metallurgy, the level of heat loss is directly related to an increase in carbon intensity. The paper noted that the inability to adapt the system to changes in consumption leads to the accumulation of CO_2 emissions even with a general decrease in production. This is fully consistent with this work's results, where an increase in unit costs in September, despite a decline in steel output, indicates a potential environmental vulnerability. Similar conclusions were noted by S.R. Paramati *et al.* (2022), who proved that reducing heat losses by 1-2% in industry contributes to reducing CO_2 emissions depending on the fuel structure. In this context, the data obtained on losses in pipelines and heat exchangers provide a reserve for reducing emissions while maintaining technological productivity. C. Tang *et al.* (2025) also indicated that consistently high specific losses – more than 0.19 Gcal/t – correlate with an increase in specific greenhouse gas emissions, especially in non-ferrous metallurgy. At the end of September, the specific consumption at the enterprise under study reached 0.1923 Gcal/t, which potentially indicates an increase in the carbon footprint in conditions of low production activity. Z. Chen *et al.* (2023) showed that structural improvements in the distribution of coolant flows, even without changing the main equipment, can reduce the level of losses by 3-5%, which reduces both direct and indirect emissions. This approach is also relevant for the enterprise under study, where loss stability indicates an insufficient level of system flexibility. Summarising, it was found that heat losses in industry have not only energy, but also environmental consequences, which can be reduced by upgrading insulation, introducing storage systems, recycling of residual heat and adaptive flow control. Integration of thermal efficiency indicators into carbon calculations will allow combining technical and environmental performance, which is key in the context of implementing the strategy of decarbonisation of the Ukrainian industry.

Conclusions

As a result of the study, it was found that the thermal efficiency of the technological cycle of PJSC Kamet-Steel in July-September 2024 remained stable, but did not meet the guidelines for energy-saving production. The average *KKWT* was 81.0%, which is lower than the recommended 85% for industrial metallurgical facilities. Accordingly, the share of heat loss reached 18.9%, which indicated the stable existence of systemic energy efficiency. This thermal imbalance indicates the inability of the infrastructure to quickly adapt to fluctuations in the production load, which is critical in high-temperature continuous technologies.

The indicator of specific heat consumption per unit of production (q), which during the analysed period varied from 0.1815 to 0.1923 Gcal/t, turned out to be an effective indicator of the functional state of the heat and power system. The increase in q in September, amid a decrease in output volumes, revealed high inertia of energy losses associated with low system flexibility to technological load reduction. Thus, specific heat consumption can be used as an operational criterion for correcting the technological regime, and for assessing environmental consequences – considering the proven relationship between q growth and carbon production intensity.

The distribution of heat losses across infrastructure components showed an asymmetric structure dominated by losses in main pipelines (7.3% of Q_{total}) and heat exchangers (5.8%), while cooling circuits and non-localised losses were 4.1% and 1.7%, respectively. This distribution reveals clearly defined critical zones, the modernisation of which can have the greatest impact on overall thermal efficiency. Reducing losses at key sites will contribute not only to improving energy efficiency, but also to reducing greenhouse emissions, which is important in the context of environmental transformation of industry. The practical significance of this conclusion lied in the possibility of developing a technical and economic model of stage reconstruction, where priority will be given to updating insulation, reconstructing heat exchangers, and optimising the operating modes of circulation circuits. Comparison of the obtained indicators with the results of international studies showed high consistency of the main parameters of energy consumption. In particular, the levels of *KKWT* and losses fully correspond to the data recorded at metallurgical enterprises in China with a similar production profile. This confirmed that even within the existing infrastructure, there is a reserve for improving energy efficiency by 5-7%, which can be implemented through local organisational and technical solutions without attracting large-scale investments.

Limitations of the study were the focus exclusively on thermal performance without considering the electricity component and associated CO_2 emissions in real terms. This limits the completeness of the assessment of the integrated energy efficiency of the enterprise. It is recommended to expand further research by including the carbon footprint, analysis of exergetic losses, and modelling the potential for multi-level residual heat utilisation in the dynamics of the production cycle. Special attention should be paid to the assessment of specific CO_2 emissions in relation to heat load, which would allow integrating energy efficiency indicators with environmental performance.

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Conflict of Interest

None.

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Ефективність теплового енергоспоживання на промислових підприємствах України в умовах екологічних обмежень

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Анотація. Метою дослідження було виявити ключові закономірності теплового енергоспоживання та сформувати аналітичну основу для оптимізації технологічних процесів з урахуванням екологічних вимог. Методологія передбачала поетапний розрахунок коефіцієнта корисного використання тепла, питомих витрат і структури теплових втрат на основі інструментальних даних теплоспоживання публічного акціонерного товариства «Камет-Сталь» за липень-вересень 2024 року. Оцінка ефективності теплового енергоспоживання на підприємстві засвідчила стабільний, однак недостатній рівень використання енергії: середній коефіцієнт становив 81,0 %, тоді як втрати тепла не знижувались нижче 18,9 %. Структурний аналіз показав, що найбільшу частку втрат становили трубопроводи (7,3 %), теплообмінники (5,8 %), охолоджувальні контури (4,1 %) та інші втрати (1,7 %), що свідчить про наявність кількох критичних зон неефективності. Питомі витрати тепла на одиницю продукції варіювалися в межах 0,1815-0,1923 Гкал/т і зростали у вересні попри зменшення обсягів виробництва, що вказує на інерційність системи постачання. На основі результатів сформовано техніко-аналітичне підґрунтя для реконструкції енергонеефективних елементів інфраструктури з орієнтовним потенціалом зниження втрат на 6-8 %. Представлені висновки також підтвердили доцільність цифрового моніторингу як інструменту стабілізації витрат і підвищення адаптивності до змін виробничого навантаження. Отримані результати можуть бути використані для розроблення техніко-економічних заходів з реконструкції теплотранспортної інфраструктури промислових підприємств, зокрема через оптимізацію режимів теплообміну, модернізацію трубопроводів і впровадження систем рекуперації залишкового тепла. Це дозволить знизити питомі витрати енергії, стабілізувати тепловий баланс і зменшити екологічне навантаження на навколишнє середовище

Ключові слова: коефіцієнт корисного використання тепла; металургійне виробництво; вуглець; трубопровідні мережі; охолоджувальні контури; рекуперація