Volume 11, Number 1, 2025

Analytical Study of Operational Efficiency of Industrial Boiler Plants Considering Building Thermophysics and Prospects for Integrating Heat Pumps

Yurii Burda[a,*], Ihor Redko[b], Yurii Pivnenko[a], Artem Cherednik[a], Roman Tkachenko[a]

[a]*O.M. Beketov National University of Urban Economy in Kharkiv, 17 Chornoglazivska St., Kharkiv, 61002, Ukraine*
[b]*Ukrainian State University of Railway Transport, Feuerbach Square 7, Kharkiv, 61050, Ukraine*

Received: April 19, 2025. Revised: May 31, 2025. Accepted: June 06, 2025.

Abstract

This study presents an in-depth analytical investigation into the operational efficiency of boiler plants in industrial enterprises, incorporating the principles of building thermophysics as a fundamental component influencing energy performance. The research focuses on the interaction between the thermophysical properties of building enclosures, architectural design parameters, and the thermal regimes of boiler equipment. It highlights how building structures significantly impact heat losses and overall energy demand within the industrial environment, emphasizing the importance of considering these aspects in the operational analysis of heating systems. The study further explores the potential of modernizing existing boiler plants through the integration of heat pump technologies. Given the increasing demand for energy-efficient and environmentally sustainable solutions, heat pumps are examined as viable alternatives or supplementary components to conventional boiler systems.

Keywords: boiler houses of industrial enterprises; energy efficiency; building thermophysics; heat losses; enclosing structures; heat supply; heat pumps.

1. Introduction

The current stage of industrial development is marked by increasing demands for the energy efficiency of production processes and engineering systems, particularly heating supply. Within the energy consumption structure of industrial enterprises, boiler installations occupy a significant share, and their operational efficiency directly affects overall energy resource expenditures and greenhouse gas emissions. Traditional approaches to the design and operation of boiler plants often neglect the impact of the thermophysical characteristics of the buildings in which these systems operate, resulting in substantial heat losses and excessive fuel consumption. Considering building thermophysics – including the thermal properties of enclosing structures, their capacity to accumulate heat, insulation performance, and the nature of thermal protection – is a necessary condition for forming an objective understanding of the energy processes within the system.

In the context of the global energy transition and the decarbonization of the industrial sector, there is growing interest in the application of innovative technologies, among which heat pumps play a particularly important role. Their integration into the heat supply structure of industrial enterprises offers opportunities for reducing the consumption of conventional energy carriers, optimizing thermal loads, and enhancing the environmental efficiency of systems. At the same time, the use of heat pumps requires careful consideration of the specific characteristics of the facility, the thermal regime of production, the structural features of the building elements, and the climatic conditions of the region.

* Corresponding author. Email address: science.yurii.burda@gmail.com

This paper should be cited as: Y. Burda, I. Redko, Y. Pivnenko, A. Cherednik, R. Tkachenko. (2025) Analytical study of operational efficiency of industrial boiler plants considering building thermophysics and prospects for integrating heat pumps. *Energy Engineering and Control Systems*, Vol. 11, No. 1, pp. 14 – 20. https://doi.org/10.23939/jeecs2025.01.014

Research dedicated to analyzing the operational efficiency of boiler plants while accounting for building thermophysics and the prospects for implementing heat pumps enables the formation of a comprehensive vision for modernizing existing systems. This approach ensures not only increased energy efficiency but also the achievement of high standards in reliability, operational stability, and environmental safety within industrial heat-generating complexes.

2. Analysis of recent research and publications

The issue of improving the energy efficiency of industrial boiler plants is actively addressed in both domestic and international scientific literature. This attention is driven by the increasing demand for energy resource savings, reduced environmental impact, and adaptation to the modern requirements of sustainable development. In recent years, researchers have particularly focused on a systemic approach to evaluating thermal processes, where not only the efficiency of boiler equipment is considered but also a range of external and internal factors, among which the thermophysical characteristics of building structures play a significant role. In the works of domestic scholars, emphasis is placed on the interrelationship between heat losses through enclosing structures, the thermal conductivity coefficients of materials, and the energy consumption level of the heat supply system [1].

In publications by international researchers, the prevailing concepts involve integrated thermal flow management, optimization of heat supply based on digital modeling, and the implementation of adaptive energy systems. A significant number of studies are devoted to the modernization of boiler plants through the integration of alternative energy sources, particularly heat pumps. These studies highlight the effectiveness of heat pumps under variable thermal load conditions and their capacity to reduce overall primary energy consumption [2].

A distinct area of research concerns the dynamics of unsteady thermal processes in industrial facilities, where the thermal inertia of buildings is taken into account. This factor has a direct impact on the selection of boiler equipment parameters and their operational modes. Despite achievements in this field, the scientific community continues to express the need for in-depth investigation of a comprehensive approach that combines building thermophysics, boiler heat engineering, and innovative thermal generation technologies – such as heat pumps – within a unified energy system of an industrial facility.

3. Goal and task setting

The primary goal of this study is to substantiate effective approaches to the operation of boiler plants in industrial enterprises by incorporating the principles of building thermophysics and to determine the prospects for the integration of heat pumps as an energy-efficient alternative or supplement to traditional heat generation systems. A comprehensive combination of the analysis of thermal characteristics of building enclosures, operational modes of thermal generation equipment, and modern heat supply technologies allows for the formation of a holistic vision for system modernization in the context of reducing energy consumption, improving thermal balance, and enhancing the environmental performance of industrial facilities.

The main tasks of the study include identifying the key factors that influence the operational efficiency of boiler plants in relation to the thermophysical properties of buildings; analyzing existing methods for assessing heat losses through building envelopes; evaluating the impact of thermal inertia in industrial buildings on the performance parameters of boiler equipment; investigating the technical and energy characteristics of heat pumps under industrial operating conditions; and developing recommendations for the integration of heat pumps into the heat supply structure, taking into account the specific features of building envelopes and the energy needs of the facility. The fulfillment of these tasks will enable the identification of the most appropriate engineering solutions for improving the energy efficiency of industrial thermal generation systems based on contemporary building science and energy technologies.

4. The main part of the study

The operational efficiency of industrial boiler plants is largely determined by the synergy between the technical parameters of heat-generating equipment, the thermal demands of the facility, and the thermophysical characteristics of the building envelope. Neglecting building thermophysics during the design or modernization of heat supply systems often leads to inefficient heat distribution, excessive loading of boiler units, and increased operational costs.

In this context, a scientific understanding of the thermal behavior of enclosing structures becomes an essential element in assessing the overall energy efficiency of the system.

Key thermophysical parameters that require consideration include thermal conductivity, specific heat capacity, vapor permeability, and the dynamic thermal inertia of enclosing components. For example, buildings with high thermal mass are capable of storing surplus heat during the daytime and releasing it during the nighttime, thus reducing peak demand on boiler systems. In such cases, it is appropriate to implement weather-compensated power regulation or variable operating regimes based on indoor thermal comfort and external climate conditions [3].

Studies indicate that, on average, up to 35% of total heat losses in industrial facilities are attributed to enclosing structures with poor insulation characteristics. Outdated brick buildings with uninsulated facades, for instance, exhibit excessive energy consumption, which – under conditions of rising fuel tariffs – creates a critical burden on the enterprise's energy budget. The application of multilayer insulation systems using materials with low thermal conductivity, such as mineral wool panels or polyurethane foam, combined with airtightness control of enclosures, enables significant reductions in heat loss without requiring the modernization of the main boiler equipment [4].

The integration of heat pumps into the heat generation infrastructure of industrial facilities presents a distinct engineering challenge that requires consideration of both the thermodynamic aspects of pump operation and their interaction with the building structure. Heat pumps operating on the reverse Carnot cycle exhibit a coefficient of performance (COP) that significantly exceeds the efficiency of traditional boilers. When using low-potential heat sources such as soil or wastewater, the COP may reach values of 3 to 5, indicating the potential to obtain 3 to 5 units of thermal energy per unit of consumed electricity.

However, the efficiency of heat pumps is directly dependent on the stability of thermal loads and the temperature regimes within the premises, which are in turn shaped by the building envelope. In cases where the building exhibits low thermal inertia or uneven heat loss distribution, cyclic loading of the heat pump's compressor occurs, reducing both its lifespan and energy efficiency. For this reason, modern engineering solutions often combine heat pumps with buffer tanks, thermal storage systems, or hybrid boilers capable of handling peak loads without compromising energy stability [5].

A notable example is the modernization of a metallurgical facility's boiler system, where, following reconstruction of the enclosing structures to improve thermal protection by approximately 45%, a 250-kW water-to-water heat pump was implemented. As a result, natural gas consumption decreased by 38%, and overall heating costs were reduced by 31%. This case demonstrates the synergistic effect of combining building thermophysics with innovative energy technologies.

The operation of industrial boiler plants is governed by complex thermodynamic processes in which the conversion of chemical energy from fuel into useful thermal energy is central to meeting internal technological and heating demands. The thermodynamic efficiency of the combustion process is primarily evaluated through metrics such as useful heat utilization, enthalpy balances, and flue gas losses. In traditional boiler systems, irreversible losses dominate – particularly in the form of heat dissipation through exhaust channels and suboptimal heat transfer in exchangers – yet these losses often disregard the thermophysical condition of the building shell, which critically influences thermal loads [6].

The incorporation of heat pumps as part of boiler plant modernization shifts the energy transformation paradigm – from direct fuel combustion to the use of low-grade heat sources via the Carnot thermodynamic cycle. Here, the energy conversion coefficient becomes central to evaluating the system's ability to repeatedly return input energy as useful heat. These processes are highly sensitive to the temperature regimes of both the heat source and the end-use environment. Building thermophysics, by shaping the thermal inertia and volumetric storage capacity of indoor spaces, acts as a passive regulator of thermodynamic performance.

For instance, high-thermal-mass buildings provide stable indoor temperatures over daily cycles, enabling heat pumps to operate under consistent load conditions and improving the system's overall COP. Conversely, in structures with low thermal inertia or uneven temperature fields, frequent compressor cycling leads to efficiency loss and accelerated wear of equipment [7].

Thus, boiler plants should not be considered merely as sources of heat, but as integral elements of a unified energy-thermodynamic environment in which heat generation, transfer, and consumption are interdependent with the thermophysical properties of the surrounding medium – including wall resistance, material conductivity, internal thermal mass, and the nature of thermal flows through building enclosures. Consequently, optimizing a boiler plant without a deep understanding of the thermal behavior of the enclosing structures is inherently limited in effectiveness. Modernization efforts must include synchronized reconstruction of building envelopes and the enhancement or supplementation of thermal generation units.

The integration of heat pumps into the thermal infrastructure of industrial facilities requires an interdisciplinary engineering approach that encompasses thermodynamics, building thermophysics, and control automation. The effectiveness of heat pumps, particularly those operating on the reverse Carnot cycle, is closely linked to the thermal behavior of the building envelope. These systems achieve high coefficients of performance (COP), particularly when utilizing low-grade energy sources such as ground heat, ambient air, or process wastewater. However, their actual efficiency is largely dependent on the stability of internal thermal conditions, which are governed by the thermophysical parameters of the enclosing structures. [8]

Buildings with high thermal inertia and efficient insulation significantly reduce the frequency of compressor cycling, thereby increasing system lifespan and maintaining high COP values. In contrast, structures with low heat accumulation capacity or non-uniform thermal loads cause frequent start-stop operation, leading to reduced energy performance and accelerated equipment wear. This highlights the importance of synchronizing building design and retrofitting strategies with the thermal characteristics of heat pump systems [9].

Modern engineering practice increasingly favors hybrid thermal generation models that combine heat pumps with conventional boiler units, thermal storage tanks, and automated control systems. Such configurations allow for adaptive load balancing, peak shaving, and optimized energy use depending on real-time thermal demand and external temperature fluctuations. For instance, during periods of mild ambient temperatures, heat pumps can handle the entire heating load, while during extreme cold spells, auxiliary boilers can provide supplementary heat to ensure uninterrupted operation and thermal comfort [10].

A representative example can be seen in the case of a metallurgical enterprise where an integrated modernization effort included the reconstruction of building envelopes and the installation of a 250-kW water-source heat pump. Following these measures, natural gas consumption was reduced by 38%, and total heating expenses dropped by over 30%. This result underscores the synergistic potential of combining advanced building thermophysics with progressive thermal technologies.

Thermophysical analysis also plays a critical role in evaluating the exergy efficiency of thermal systems. Traditional boiler plants are characterized by substantial exergy losses, especially when operating with low-temperature return water. Heat pumps, by contrast, are inherently more efficient in low-temperature applications such as underfloor heating or pre-heated ventilation air, as they minimize exergy destruction and align thermal supply more closely with demand.

From a thermodynamic standpoint, the building's ability to store and buffer heat contributes to stabilizing operational modes and optimizing energy recovery. Systems with high volumetric thermal capacity and well-regulated insulation can function as passive energy stabilizers, thereby enhancing the thermodynamic stability and energy responsiveness of the entire thermal network.

Furthermore, the deployment of intelligent control systems is critical for unlocking the full potential of combined boiler–heat pump installations. Automation technologies based on SCADA platforms, IoT sensor networks, and machine learning algorithms allow for real-time monitoring, predictive control, and adaptive optimization. These systems enable not only efficient thermal management but also synchronization with energy tariffs, weather forecasts, and production cycles.

Feedback systems equipped with sensors for humidity, solar radiation, CO_2 levels, and infrared thermography facilitate multidimensional control over the indoor climate. This is especially important in industrial processes where environmental conditions directly impact production quality. In such cases, the integration of thermophysical knowledge with control systems leads to energy harmonization – where both the equipment and the building envelope adapt dynamically to optimize performance.

By adopting such comprehensive strategies, industrial heat supply systems evolve from isolated heat sources into intelligent, thermally adaptive ecosystems. These systems achieve maximum efficiency not by increasing energy input but by dynamically balancing generation, storage, and consumption through thermophysically informed design and smart control.

The prospects for integrating heat pumps into industrial heating systems are highly promising, offering a range of advantages in terms of energy efficiency, cost reduction, and environmental sustainability. As industries face increasing pressure to reduce energy consumption and minimize environmental impacts, heat pumps present a viable solution by utilizing renewable energy sources such as geothermal and ambient air heat. This enables a significant reduction in reliance on conventional fossil fuels, contributing to a greener, more sustainable energy landscape. One of the key advantages of integrating heat pumps is their ability to operate efficiently even at low ambient temperatures, making them ideal for regions with colder climates. By extracting heat from the environment, heat pumps provide a highly effective means of maintaining consistent heating throughout the year, ensuring stable operational conditions for industrial processes.

The thermophysical characteristics of buildings directly impact the efficiency of heating systems, as they determine how well heat is retained or lost through walls, roofs, windows, and other building elements. The integration of heat pumps into industrial heating systems, when combined with a detailed analysis of building thermophysics.

The generalized data and characteristics are presented in Table 1.

Table 1. Dependence of the efficiency.

Temperature (K)	Boiler Efficiency (%)	COP of Heat Pump (Coefficient of Performance)	Energy Consumption (kWh)
278.15	85	3.2	500
283.15	84	3.3	480
288.15	82	3.5	460
293.15	80	3.8	440
298.15	77	4.0	420
303.15	75	4.1	400
308.15	72	4.3	380
313.15	70	4.4	360
318.15	68	4.5	340
323.15	65	4.6	320

Below is the graph showing the dependence of the efficiency of boiler houses and heat pumps on the ambient temperature and energy consumption (Fig. 1).

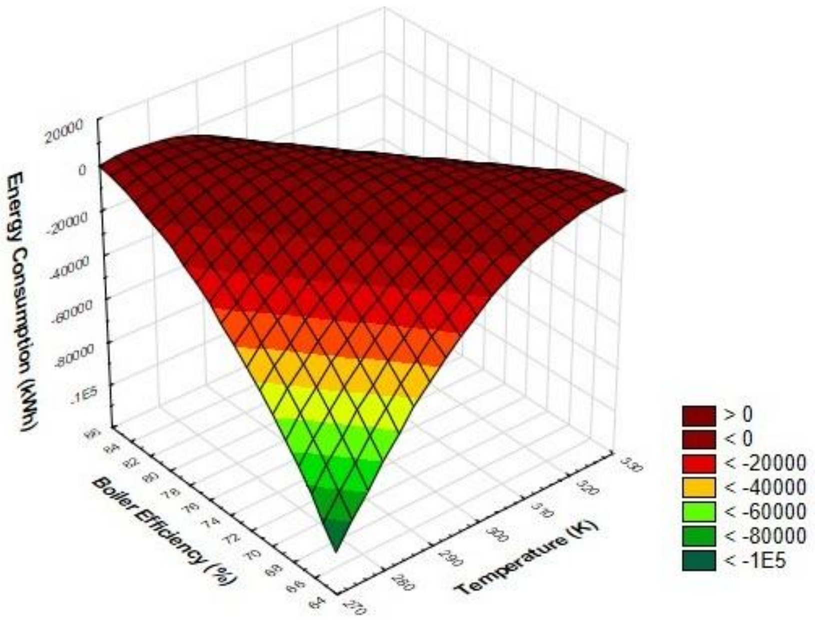

Fig.1. Dependence of efficiency of boiler houses and heat pumps on the ambient temperature and energy consumption.

Further, the role of building thermophysics extends to the optimization of heat exchange processes in industrial heating systems. By understanding how heat moves through different materials and building structures, engineers can design more efficient boiler and heat pump systems, reducing energy consumption while maintaining optimal thermal comfort inside the industrial facility. The continuous monitoring of these thermophysical properties, along with advancements in building materials and insulation technologies, will play a pivotal role in future innovations aimed at boosting the energy efficiency of industrial heating systems.

Thus, a comprehensive approach to the analysis of boiler houses, based on considering the thermophysical characteristics of buildings and the potential for using heat pumps, allows for the formulation of an effective energy strategy for industrial enterprises. Further research should focus on the development of adaptive heating control models using real-time monitoring technologies, artificial intelligence for load forecasting, and digital twins of facilities, which will enable achieving even higher levels of energy efficiency, reliability, and environmental safety in the industrial sector.

5. Conclusion

The analysis of the operational efficiency of boiler houses at industrial enterprises, taking into account building thermophysics and the integration of heat pumps, allows for several key conclusions regarding the improvement of energy efficiency and the reduction of operating costs in industrial heating systems.

In conclusion, the integration of building thermophysics with industrial boiler plant operations and heat pump technologies offers a comprehensive approach to enhancing energy performance. It enables the development of adaptive systems that can dynamically adjust to varying environmental conditions, resulting in reduced energy consumption, extended equipment life, and improved environmental sustainability.

Increasing efficiency through the integration of technologies. The implementation of heat pumps into the heating system of industrial enterprises significantly reduces energy consumption by utilizing renewable energy sources, optimizing heat usage even at low ambient temperatures.

The dependence of efficiency on temperature fluctuations. The study found that as the ambient temperature rises, the efficiency of boiler houses decreases, while the coefficient of performance (COP) of heat pumps increases. This highlights the importance of adaptive control systems that can automatically regulate the operation of boilers and pumps depending on external conditions.

The implementation of combined heat generation systems significantly reduces fuel and energy resource costs, which is a crucial aspect in today's economic realities. With proper design and system configuration, substantial savings can be achieved compared to traditional heating methods.

References

[1] Pyarimohan Dehury, Shahil Chaudhari, Tamal Banerjee, Sarit Kumar Das. Prediction of thermophysical properties of deep eutectic solvent-based organic nanofluids: A machine learning approach. Journal of Molecular Liquids. Volume 411, 1 October 2024, 125809. https://doi.org/10.1016/j.molliq.2024.125809

[2] Yichuan He, Yanhui Feng, Lin Qiu, Dawei Tang. Data-driven approach augmented by attention mechanism in critical and boiling thermophysical properties prediction of fluorine/chlorine-based refrigerants. Energy. Volume 306, 15 October 2024, 132490. https://doi.org/10.1016/j.energy.2024.132490

[3] Bernadeta Jasiok and all. Thermophysical properties of the SPC/E model of water between 250 and 400 K at pressures up to 1000 MPa. Fluid Phase Equilibria. Volume 584, September 2024, 114118. https://doi.org/10.1016/j.fluid.2024.114118

[4] Rui Zhang, Xu, Lin Chen. Asymptotic thermophysical behaviors of near-critical fluid under parameter scaling. International Journal of Heat and Fluid Flow. Volume 108, September 2024, 109442. https://doi.org/10.1016/j.ijheatfluidflow.2024.109442

[5] Sohail A. Khan, T. Hayat, A. Alsaedi. Chemically reactive flow beyond constant thermophysical characteristics. Case Studies in Thermal Engineering. Volume 61, September 2024, 104980. https://doi.org/10.1016/j.csite.2024.104980

[6] M. Abd El-Hamid, Gaosheng Wei. Effect of varying the thermophysical properties of phase change material on the performance of photovoltaic/thermal-PCM hybrid module numerically. Journal of Energy Storage. Volume 86, Part B, 10 May 2024, 111326. https://doi.org/10.1016/j.est.2024.111326

[7] Sujata Kalsi and all. Thermophysical properties of nanofluids and their potential applications in heat transfer enhancement: A review. Arabian Journal of Chemistry. Volume 16, Issue 11, November 2023, 105272. https://doi.org/10.1016/j.arabjc.2023.105272

[8] Rupali Tiwari and all. Investigation of thermophysical properties of Turkey oak particleboard for sustainable building envelopes. Developments in the Built Environment. Volume 16, December 2023, 100228. https://doi.org/10.1016/j.dibe.2023.100228

[9] Fatemeh Zarei-Jelyani, Fatemeh Salahi, Behnaz Rahmatmand, Mohammad Reza Rahimpour. 3 - Thermophysical properties of natural gas hydrates. Advances in Natural Gas: Formation, Processing, and Applications. Volume 3: Natural Gas Hydrates. 2024, Pages 47-63. https://doi.org/10.1016/B978-0-443-19219-7.00006-0

[10] Bo Jin, Shuhong Liu, Kai Xu, Qiang Lu b, Yong Du. Thermophysical properties in the Al-Cu-Ag system: A combined CALPHAD and first-principles study. Journal of Molecular Liquids. Volume 370, 15 January 2023, 121001. https://doi.org/10.1016/j.molliq.2022.121001

Аналітичне дослідження ефективності експлуатації котелень промислових підприємств із урахуванням будівельної теплофізики та перспективи інтеграції теплових насосів

Юрій Бурда[a], Ігор Редько[b], Юрій Півненко[a], Артем Череднік[a], Роман Ткаченко[a]

[a]*Харківський національний університет міського господарства імені О.М. Бекетова, вул. Чорноглазівська, 17, Харків, 61002, Україна*

[b]*Український державний університет залізничного транспорту, майдан Фейєрбаха 7, Харків, 61050, Україна*

Анотація

У статті представлено аналітичне дослідження ефективності експлуатації котелень промислових підприємств з урахуванням будівельної теплофізики та перспектив інтеграції теплових насосів у систему теплопостачання. Важливість такого підходу полягає в можливості зниження енергоспоживання та покращення енергетичної ефективності промислових котелень за рахунок оптимізації використання теплових ресурсів, зокрема через впровадження сучасних технологій, таких як теплові насоси, які забезпечують використання відновлювальних джерел енергії. Будівельна теплофізика є ключовим елементом при проектуванні та аналізі роботи котелень, оскільки вона дозволяє врахувати теплопередавальні характеристики матеріалів та будівельних конструкцій, що суттєво впливають на загальну ефективність системи теплопостачання. Зокрема, правильний підбір матеріалів для утеплення будівель, а також врахування теплових втрат та нагрівальних характеристик дозволяє значно підвищити ефективність роботи котелень та зменшити витрати на енергоресурси. Таким чином, інтеграція теплових насосів у котельні промислових підприємств із урахуванням будівельної теплофізики є важливим кроком на шляху до сталого розвитку та зниження енергетичних витрат, що сприяє підвищенню енергоефективності та екологічної безпеки промислових об’єктів.

Ключові слова: котельні промислових підприємств; енергоефективність; будівельна теплофізика; теплові втрати; огороджувальні конструкції; теплопостачання; теплові насоси; енергоефективність.