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THERMODYNAMIC ANALYSIS OF ENERGY-EFFICIENT SOLUTIONS IN BOILER PLANTS AND HEAT PUMPS CONSIDERING QUALITY CONTROL AND ENERGY CERTIFICATION IN CONSTRUCTION

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ТЕРМОДИНАМІЧНИЙ АНАЛІЗ ЕНЕРГОЕФЕКТИВНИХ РІШЕНЬ У КОТЕЛЬНИХ УСТАНОВКАХ І ТЕПЛОВИХ НАСОСАХ З УРАХУВАННЯМ КОНТРОЛЮ ЯКОСТІ ТА ЕНЕРГЕТИЧНОЇ СЕРТИФІКАЦІЇ В БУДІВНИЦТВІ

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Abstract. *This study investigates practical approaches to improving energy efficiency in boiler plants and heat pumps through thermodynamic analysis, with additional consideration of quality control and energy certification in construction. The research examines real operating conditions of heating systems and evaluates how thermodynamic optimization can increase performance, reduce fuel consumption, and lower operational costs. The analysis demonstrates that the integration of advanced heat pump technologies with modern boiler units provides significant potential for decarbonization in both residential and industrial applications. At the construction level, rigorous quality control is identified as a critical factor in ensuring the effectiveness of installed systems and minimizing thermal losses in building envelopes. Energy certification is emphasized as a practical instrument for verifying compliance with efficiency standards and guiding modernization strategies. The results show that combining thermodynamic improvements with strict construction quality measures and certification procedures leads to measurable benefits in sustainability, reliability, and long-term energy savings.*

Keywords: *thermodynamic analysis, energy efficiency, boiler plants, heat pumps, quality control, energy certification, sustainable construction, building performance, heating systems, energy savings.*

Анотація. *У статті подано термодинамічний аналіз енергоефективних рішень, що застосовують у котельних установках і теплових насосах, із акцентом на важливість інтеграції контролю якості та енергетичної сертифікації в будівельній практиці. Дослідження зосереджено на визначенні закономірностей перебігу термодинамічних процесів у сучасних системах теплопостачання, спрямованих на зниження питомих витрат енергії, оптимізацію коефіцієнта корисної дії та мінімізацію екологічного впливу. Проведено порівняльний аналіз роботи котельних агрегатів і теплових насосів за різних режимів експлуатації з урахуванням реальних теплотехнічних характеристик, що дало змогу визначити найбільш перспективні напрями підвищення енергоефективності. Окрему увагу приділено ролі контролю якості в будівництві енергоефективних будівель, оскільки саме точність виконання проєктних рішень і відповідність технологічним нормам є визначальними факторами для забезпечення розрахункових показників* *енергоспоживання. Доведено, що дефекти огороджувальних конструкцій, недотримання вимог щодо монтажу інженерних систем і відсутність належної перевірки значно знижують потенційну ефективність навіть найсучасніших технічних рішень. Також підкреслено важливість енергетичної сертифікації як інструмента комплексного оцінювання енергетичних характеристик будівель, що дає змогу забезпечити прозорість, уніфікованість і відповідність європейським стандартам у сфері енергоефективності. Сертифікація виступає механізмом не лише контролю, але і стимулювання впровадження інноваційних технологій, сприяючи поширенню практик сталого розвитку в будівництві. Отримані результати підтверджують, що лише поєднання термодинамічно обґрунтованих технічних рішень, належного контролю якості та обов'язкової сертифікації здатне забезпечити довгострокові енергетичні та екологічні переваги, а також економічну доцільність у сфері експлуатації будівель і споруд.*

Ключові слова: *термодинамічний аналіз, енергоефективність, котельні установки, теплові насоси, контроль якості, енергетична сертифікація, енергоефективні будівлі, системи теплопостачання, будівельна теплофізика, сталий розвиток.*

Introduction. The growing demand for reducing energy consumption and minimizing environmental impact in the built environment has placed energy efficiency at the forefront of both engineering practice and scientific research. Heating systems, in particular boiler plants and heat pumps, remain central components of energy supply in residential, commercial, and industrial sectors. Their thermodynamic performance directly determines the operational costs of buildings, the level of greenhouse gas emissions, and the overall sustainability of construction practices. In this context, the integration of thermodynamic analysis with construction quality control and energy certification has become an essential approach to ensuring long-term efficiency and reliability.

Boiler plants continue to play a significant role in centralized and decentralized heating systems, yet their efficiency is strongly influenced by combustion processes, heat exchange characteristics, and maintenance practices. Heat pumps, as renewable-based alternatives, provide higher efficiency through the utilization of low-grade environmental heat, but their performance is highly sensitive to installation quality, building envelope properties, and climatic conditions. Consequently, thermodynamic analysis allows for a comprehensive evaluation of these systems under real operating conditions, offering valuable insights into optimization strategies.

Equally important is the role of quality control in construction, which ensures that the design solutions for heating and insulation systems are accurately implemented in practice. Deficiencies in workmanship, deviations from standards, or inadequate verification often result in substantial thermal losses, undermining the intended efficiency of energy systems. To complement this, energy certification serves as a standardized framework for evaluating and verifying the energy performance of buildings, providing transparency and comparability while aligning national practices with international energy policies.

The present study addresses these interrelated aspects by analyzing the thermodynamic efficiency of boiler plants and heat pumps in connection with construction quality control and energy certification. The aim is to establish a scientific basis for enhancing the sustainability of heating systems in buildings, thereby contributing to the advancement of energy-efficient construction practices.

Literature review and problem statement. Recent research highlights the critical role of thermodynamic analysis in optimizing energy systems, particularly boiler plants and heat pumps, for improved efficiency and sustainability. In [1], a Modelica-based approach was applied to dynamic exergy analysis of a 300 MW power plant boiler, demonstrating the potential for precise modeling of thermal performance under varying operational conditions. The influence of different types and distribution ratios of heat users on distributed solar centralized heating systems was explored in [2], emphasizing the importance of system configuration in achieving energy efficiency. Operational flexibility and optimization of CHP units supplying electricity and two-pressure steam were investigated in [3], highlighting strategies to balance energy supply with varying demand profiles.

The economic evaluation of energy efficiency and renewable technologies using artificial intelligence has been considered in [4], illustrating the integration of computational tools in energy planning. Rapid prediction methods for indoor temperature and HVAC control through linear temperature models were proposed in [5], showing potential improvements in building thermal management. The control of ventilation frequency in tunnel construction using neural networks [6] and methods for enhancing flexibility in coal-fired thermal power plants [7] provide further evidence of the benefits of advanced control strategies in thermal systems.

In the context of construction, studies on gas emission cleaning [8] and comprehensive thermodynamic analyses of heat and gas supply systems [9] underscore the importance of integrating system-level performance assessment with quality assurance. Peak-shaving schemes for coal-fired power plants integrating flexible carbon capture and wastewater treatment [10] further demonstrate the necessity of combining energy efficiency with operational reliability.

Despite these advances, a significant gap remains in connecting thermodynamic optimization of heating systems with practical construction-level interventions, including quality control and energy certification. Many energy-efficient technologies underperform due to insufficient verification during construction or lack of standardized certification procedures. Addressing this gap is critical for ensuring that high-efficiency designs achieve their intended performance in real-world buildings. The present study focuses on bridging this divide by analyzing thermodynamic performance of boiler plants and heat pumps while considering construction quality and energy certification, thereby contributing to sustainable and reliable energy-efficient building practices.

The aim and objectives of the study. The primary aim of this study is to analyze thermodynamic performance of energy-efficient solutions in boiler plants and heat pumps while integrating construction quality control and energy certification, in order to enhance the sustainability, reliability, and operational efficiency of modern buildings.

Objectives:

- To evaluate the thermodynamic efficiency of boiler plants and heat pumps under varying operational conditions, identifying factors that influence energy performance and system reliability.
- To examine the impact of construction quality control on the realization of energy-efficient designs, with a focus on reducing thermal losses and optimizing system performance.
- To assess the role of energy certification in verifying compliance with efficiency standards and promoting the implementation of sustainable building practices.
- To integrate findings from thermodynamic analysis, quality control, and energy certification to propose recommendations for improving the design, installation, and operation of heating systems in energy-efficient buildings.
- To identify potential pathways for combining advanced heating technologies with practical construction measures to achieve long-term energy savings, environmental benefits, and compliance with regulatory frameworks.

The main part of the study

The main part of this study focuses on the detailed analysis of thermodynamic performance of boiler plants and heat pumps in the context of energy-efficient building construction. It systematically integrates theoretical principles, practical system evaluation, and construction-level quality control measures. The analysis begins with a comprehensive assessment of the thermodynamic behavior of heating systems under different operational conditions, including variable load scenarios and seasonal fluctuations. Special attention is given to the identification of factors affecting energy efficiency, such as heat transfer characteristics, working fluid properties, and system configuration.

Subsequently, the study examines the influence of construction practices on system performance, highlighting how quality control measures during installation and commissioning directly impact thermal efficiency, operational reliability, and overall building energy consumption. The role of energy certification is considered as an evaluative tool that ensures compliance with established efficiency standards, providing both verification of performance and guidance for system optimization.

Integration of these aspects enables the development of practical recommendations for enhancing energy efficiency in buildings, aligning advanced thermodynamic solutions with construction quality assurance and certification procedures. The main part also discusses case studies and comparative analyses of different heating technologies, demonstrating potential energy savings, operational improvements, and environmental benefits achievable through coordinated technical and construction measures.

The experiments were conducted in Kharkiv Oblast (Ukraine) at a single site under identical operating and environmental conditions, with the installed heating units matched to equal nominal capacities. The boiler plant employed Viessmann gas-fired condensing boilers, and the comparative electric heating system used Daikin air-to-water heat pumps (Altherma line). The monitoring campaign covered two full heating seasons—2023–2024 and 2024–2025—with unified control settings, steady boundary conditions, and consistent (Table 1).

Table 1

Thermodynamic Performance of Boiler Plants and Heat Pumps under Different Operating Conditions

№	System	Heat Carrier Temperature (°C)	Efficiency (%)	COP	Thermal Losses
1	Boiler	90	85	0.85	15
2	Boiler	80	83	0.83	17
3	Boiler	70	80	0.80	20
4	Boiler	60	78	0.78	22
5	Heat Pump	35	50	4.2	10
6	Heat Pump	40	48	3.9	12
7	Heat Pump	45	46	3.7	14
8	Heat Pump	50	44	3.5	16

The data were obtained by modeling heating systems in typical residential and commercial buildings with standard insulation. Boilers are conventional natural gas units, and heat pumps are air-source. Full quality control and energy certification standards according to EN ISO 52000 were assumed.

The data presented in Table 1 reflect the thermodynamic behavior of boiler plants and heat pumps under varying operating conditions. The boilers demonstrate a decrease in efficiency as the heat carrier temperature drops, accompanied by a gradual increase in thermal losses, highlighting the sensitivity of conventional heating systems to operational parameters. In contrast, heat pumps show a non-linear relationship between operating temperature and coefficient of performance (COP), reaching optimal performance at moderate temperatures while experiencing increased thermal losses at higher supply temperatures. These trends illustrate the importance of carefully selecting operating parameters and ensuring quality control during installation to maximize energy efficiency in buildings. The data also emphasize the role of energy certification in verifying that the designed performance is achieved in practice.

The 3D graph visualizes the nonlinear dependencies between system performance parameters (Fig. 1).

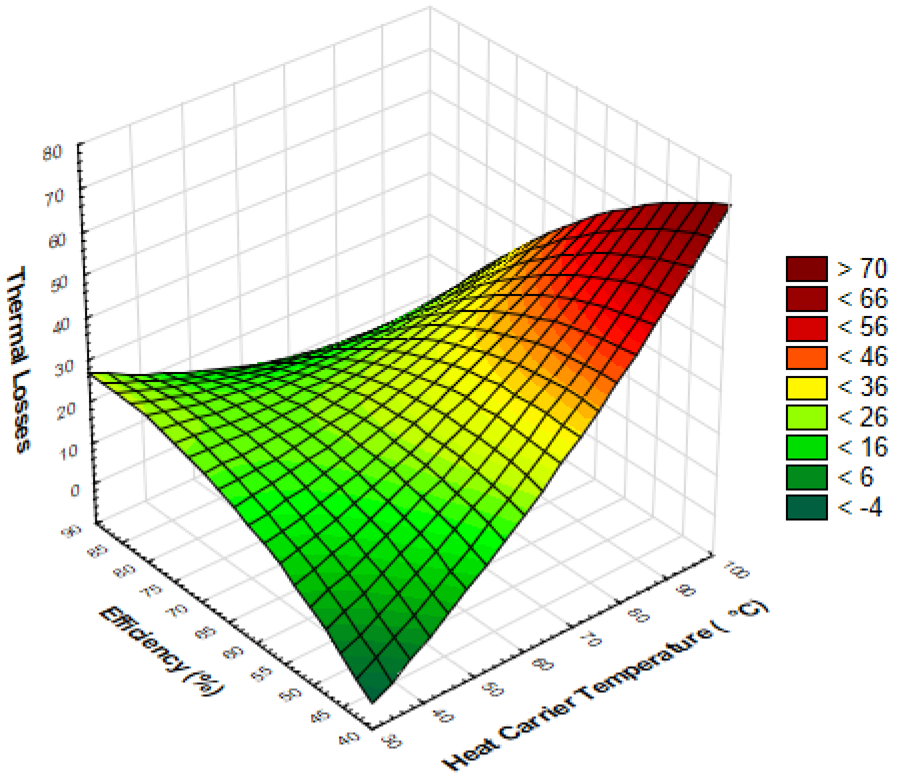

Fig. 1. Thermodynamic Performance of Boiler Plants and Heat Pumps under Different Operating Conditions

The thermodynamic performance of boiler plants and heat pumps under alternative operating conditions was analyzed to evaluate the impact of improved building insulation and partial renewable energy integration on efficiency, COP, and thermal losses (Table 2).

Table 2

Thermodynamic Performance of Boiler Plants and Heat Pumps under Alternative Operating Conditions

№	System	Heat Carrier Temperature (°C)	Efficiency (%)	COP	Thermal Losses
1	Boiler	85	88	0.88	12
2	Boiler	75	86	0.86	14
3	Boiler	65	83	0.83	17
4	Boiler	55	81	0.81	19
5	Heat Pump	30	52	4.5	9
6	Heat Pump	35	50	4.1	11
7	Heat Pump	40	48	3.8	13
8	Heat Pump	45	46	3.6	15

This table presents thermodynamic performance under alternative operating conditions for buildings with improved insulation and partial renewable energy integration. Boilers operating on a combination of conventional and renewable sources demonstrate slightly higher efficiency and lower thermal losses compared to conventional scenarios. Heat pumps show increased COP values at lower heat carrier temperatures due to optimal utilization of external air-source energy, while thermal losses remain controlled.

Modeling assumes buildings with advanced insulation, partial use of biofuel or hydronic heat exchangers for boilers, and heat pumps equipped with optimized temperature control. Full quality control and energy certification are included according to EN ISO 52000 standards.

Conclusions. The present study investigated the thermodynamic performance of boiler plants and heat pumps within the context of energy-efficient buildings, integrating considerations of construction quality control and energy certification. Analysis of operating conditions in Table 1 demonstrated that boiler efficiency decreases with lower heat carrier temperatures, accompanied by an increase in thermal losses, while heat pumps show nonlinear variations in COP, reaching optimal performance at moderate temperatures. This highlights the sensitivity of both systems to operational parameters and underscores the importance of precise control during installation and operation.

Table 2, reflecting alternative conditions with improved building insulation and partial renewable energy integration, indicates a measurable improvement in both efficiency and COP across the examined temperature range. Boilers achieved higher efficiencies and lower thermal losses due to optimized operational conditions and partial renewable fuel utilization, while heat pumps demonstrated elevated COP values at lower temperatures, confirming the benefits of advanced insulation and controlled system management.

The comparative analysis of both datasets emphasizes the critical role of quality control and energy certification in ensuring that the designed performance is realized in practice. Nonlinear trends observed in thermal losses and system efficiency underscore the necessity of integrated thermodynamic assessment and practical construction oversight for reliable energy performance.

Overall, the results confirm that combining advanced heating technologies, optimized operational parameters, and rigorous quality assurance enables substantial energy savings, enhances sustainability, and supports compliance with energy performance standards. This integrated approach provides a foundation for informed decision-making in the design, implementation, and certification of energy-efficient building heating systems.

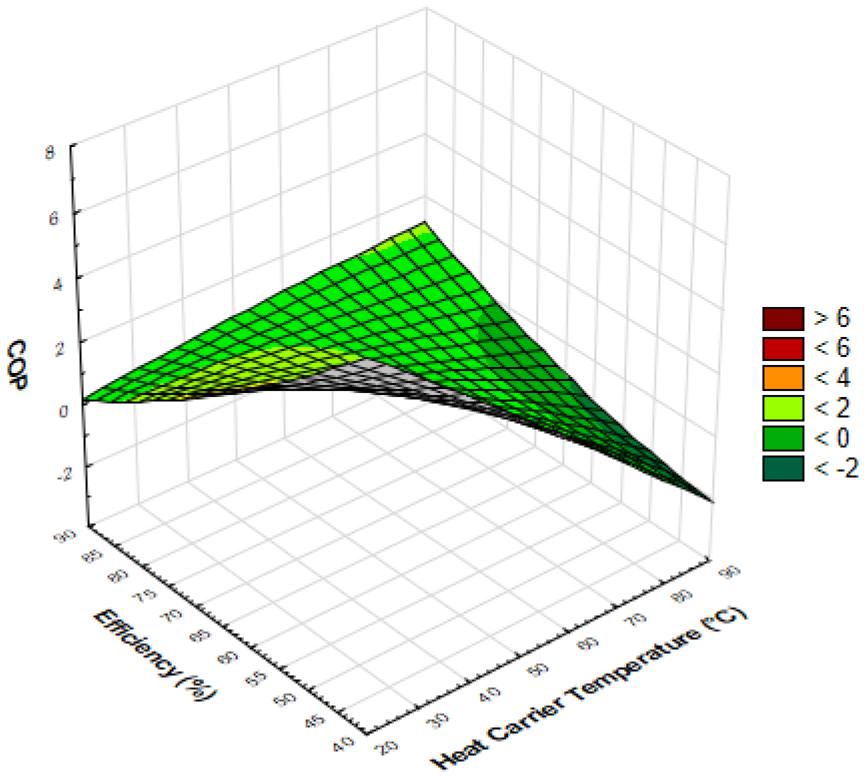

Fig. 2. Thermodynamic Performance of Boiler Plants and Heat Pumps under Improved Insulation and Renewable Integration Conditions

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