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Improving technical and economic solutions for the reconstruction of enterprises in the construction industry

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Abstract. The purpose of the study was to substantiate and improve technical and economic solutions for the reconstruction of enterprises in Ukraine's construction industry, taking into account current trends in energy efficiency, the digitalisation of production processes, and the transition to the use of alternative fuels. The study had a theoretical and analytical nature and was conducted using computational-and-evaluative, structural-system, analytical, and comparative methods. The methodological basis comprised the international standards ISO 50001:2018, 14044:2006, 15686-5:2017, and the DSTU EN 16247-3:2021. Computational-and-evaluative modelling of the heat-generation systems of a boiler house with a capacity of 10 t of steam/hour showed that, when switching from natural gas to biomass, specific energy costs decreased by 21.2%, and CO_2 emissions – by 80.4%; when using pyrocarbon – by 17.3% and 58.9%, respectively. The technical efficiency coefficient was 81.7% for biomass, 84.2% for pyrocarbon, and 86.4% for natural gas. The integral efficiency indicator $E_{(int)}$ exceeded the baseline level of 1 – reaching 1.28 for biomass and 1.19 for pyrocarbon. The "costs – emissions" diagram with a coefficient of determination $R^2 > 0.9$ demonstrated a stable negative correlation between economic costs and environmental emissions, outlining an optimality zone below 450 UAH/GJ and 0.025 t CO_2/GJ. The harmonisation of the provisions of the standards ensured methodological consistency between energy planning, life-cycle assessment, and cost management, which made it possible to form an integrated decision-making model for the reconstruction of industrial facilities. The proposed combination of digital energy management, environmental-economic balancing, and life-cycle costing confirmed the possibility of achieving energy efficiency ⩾0.85 under conditions of minimising the cost of heat generation and decarbonising production processes. The practical significance lay in the possibility of applying the obtained results for the modernisation of construction enterprises and the adaptation of Ukrainian industry to the EU sustainable-development requirements

Keywords: energy efficiency; alternative fuels; energy management; life cycle; decarbonisation

Introduction

The relevance of the study was driven by the need to improve technical and economic solutions for the reconstruction of enterprises in the construction industry under conditions of energy transformations, production digitalisation, and the need to transition to sustainable development. Ukraine's construction industry is undergoing profound structural modernisation, driven both by wartime destruction of infrastructure and by global trends in decarbonisation and energy efficiency. In this context, the reconstruction of operating enterprises acquired not only technical but also strategic significance – as an instrument for restoring industrial

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potential and simultaneously implementing innovative technologies aimed at reducing energy costs and increasing competitiveness.

Issues of innovative development of enterprises in the construction complex have been actively studied in economic and technical science. In particular, M. Mudra & Yu. Krychevska (2024) substantiated approaches to information-and-analytical support for the economic assessment of innovative solutions in construction, emphasising the role of digital indication and automated management systems. Similar trends were outlined by U. Andrusiv *et al.* (2024), who considered environmental modernisation as a key technology for renewing production and forming the innovative potential of the sector. In turn, H. Zhovtiak & R. Bohdanov (2025) emphasised that digitalisation became a determining factor in the development of construction enterprises, providing new approaches to managing resources, production processes, and financial flows. At the same time, as noted by L. Romanova & Y. Grigerman (2024), contemporary economic challenges drove the need to rethink the very concept of reconstruction – from a simple renewal of fixed assets to the implementation of comprehensive technical and economic models that took into account energy security, environmental friendliness, and investment efficiency. In this respect, the combination of technological innovations, such as Building Information Modelling (BIM), with in-depth economic assessments of reconstruction options became important.

The potential of BIM-oriented technical and economic frameworks was thoroughly confirmed in the work of O. Doukari *et al.* (2023), where a model of comparative analysis of building-renovation strategies was proposed, which made it possible to optimise costs, implementation timelines, and energy-efficiency indicators on the basis of digital modelling. The authors proved that the integration of BIM technologies into reconstruction processes ensured not only the visualisation of design solutions, but also a multi-criteria assessment of reconstruction options, including by life-cycle and operating-cost criteria. At the same time, A. Ebekozien & M. Samsurijan (2024) emphasised the importance of economic incentives for implementing digital innovations through tax benefits, grant programmes, and public-private partnerships, which contributed to faster adoption of new technologies in the construction sector. Summarising existing approaches, W. Hu *et al.* (2022) noted in the systematic review that the combination of BIM with Industry 4.0 principles, Internet of Things technologies, and digital twins formed the basis for creating "smart" enterprises in which continuous data exchange took place between design, production, and operation. A separate research direction concerned the integration of energy technologies into reconstructed facilities. E. McLaughlin *et al.* (2022) proved the effectiveness of energy-saving solutions in industrial combustion systems, which directly correlated with the modernisation of thermal engineering equipment at construction enterprises. F. Yu *et al.* (2023), in a study of the housing stock of European cities, showed that the technical and economic analysis of heating strategies made it possible to minimise costs while maintaining thermal comfort. Subsequently, L. Chen *et al.* (2024) proposed a thermo-economic model using thermal storage and photovoltaic collectors, which made it possible to reduce operating costs and increase the share of renewable energy. Summarising the results of the analysed studies, it can be stated that modern approaches to reconstructing construction-industry enterprises were based on integrating digital, energy, and economic components into a single innovation-development management system. The use of BIM technologies, digital twins, and energy-efficient design systems ensured not only cost optimisation, but also increased environmental sustainability and energy autonomy of production.

Despite the comprehensiveness of modern approaches, the analysed studies insufficiently covered the practical aspects of harmonising technical, economic, and regulatory standards during the implementation of reconstruction projects for construction-industry enterprises. In particular, there was a lack of systemic methods for integrating energy-technology solutions based on alternative fuels with the requirements of national and international energy-efficiency and environmental-safety standards. Issues of quantitative assessment of the effectiveness of reconstruction measures using life-cycle indicators, as well as models for assessing risks and uncertainty of investment decisions in long-term modernisation programmes, also remained underdeveloped. The absence of unified methodological foundations for aligning technical solutions with economic criteria constrained the formation of a unified reconstruction-planning system, which required further scientific substantiation and practical verification under the conditions of Ukrainian construction-industry enterprises.

The purpose of the study was to develop and scientifically substantiate improved technical and economic approaches to the reconstruction of enterprises in Ukraine's construction industry, taking into account current trends in increasing energy efficiency, digital transformation of production, and the introduction of alternative fuel resources. To achieve this purpose, the following tasks were defined: to investigate the theoretical foundations of technical and economic reconstruction of construction-industry enterprises; to assess the impact of implementing alternative fuels and energy-saving technologies on production efficiency; to generalise the factors that determined the economic feasibility and environmental advantages of reconstruction processes under contemporary conditions.

Materials and Methods

The study had a theoretical and analytical nature and was based on a systemic synthesis of scholarly approaches to improving technical and economic solutions for the reconstruction of enterprises in the construction industry. The methodological basis comprised analytical, structural-system, comparative, and computational-and-evaluative methods, which made it possible to reveal the relationship between the energy, technical, and economic aspects of modernising industrial facilities. The analytical method was applied for a critical review of scholarly sources and regulatory and technical documents that regulated the principles of reconstructing production systems in accordance with international standards – ISO 14044:2006 (2006), ISO 15686-5:2017 (2017), ISO 50001:2018 (2018), and DSTU EN 16247-3:2015 (2015). The structural-system approach made it possible to consider the reconstruction of construction-industry enterprises as a multi-level system in which technical renewal, digital management, energy modernisation, and economic efficiency acted as interconnected components of a single production-and-innovation loop. Such an approach made it possible to integrate the results of technical calculations, energy-monitoring data, and economic assessments into a common decision-making model oriented towards minimising life-cycle costs and maximising the energy-efficiency indicator η. This indicator was used in the work as the main calculated characteristic for assessing the effectiveness of each reconstruction option, and was formally expressed by ratio (1):

$$\eta = \frac{Q_{useful}}{Q_{int}} \times 100\%, \quad (1)$$

where Q_{useful} – the volume of useful thermal energy utilised; Q_{int} – total fuel energy expenditure.

Calculations under formula (1) were performed for each type of fuel – natural gas, biomass, and pyrocarbon – considering the calorific value and the adopted baseline efficiency coefficients, which ensured the unity of comparison criteria. The comparative method was applied to generalise qualitative and quantitative differences between traditional technologies based on natural-gas combustion and modern solutions oriented towards the use of alternative fuels – biomass and pyrocarbon. The analysis covered typical models of reconstruction of energy facilities similar to medium-capacity steam boiler houses (10 t of steam per hour), shaft kilns for lime burning, and drying units for building materials, in which a transition from fossil fuel to biofuel was possible. The selection of these facilities was driven by the significant specific share in the structure of energy consumption of construction-industry enterprises, the homogeneity of technological processes in which thermal energy was the main energy resource, as well as the stability of load regimes and the possibility of modular renewal of fuel systems. Such conditions ensured the representativeness of the models for assessing the impact of reconstruction measures on energy efficiency and the cost of thermal energy.

The comparison of energy efficiency and economic feasibility was performed taking into account the calorific value of the fuel, the efficiency coefficient of the installation, specific energy costs, the CO_2 emission factor, life-cycle cost, equipment service life, and investment volume. The study considered three typical models: Model A – a steam boiler house with a capacity of 10 t/h operating on natural gas (baseline option); Model B – a modernised boiler house with a biomass burner unit; Model C – a combined pyrolysis-type thermal installation using pyrocarbon. This approach ensured the reproduction of real operating conditions of industrial facilities and made it possible to quantitatively assess the effect of switching to alternative fuels according to energy, economic, and environmental criteria. Such facilities were considered not as specific enterprises, but as theoretically modelled systems that made it possible to trace patterns of changes in energy efficiency, unit cost of thermal energy, and the level of CO_2 emissions. To ensure the homogeneity of calculation conditions, the following energy characteristics of fuels were adopted: calorific value of natural gas – 47.5 MJ/kg, biomass – 18.5 MJ/kg, pyrocarbon – 29.2 MJ/kg. The baseline technical efficiency coefficients (η_t) in the modelling were, respectively, 86.4% for natural gas, 81.7% for biomass, and 84.2% for pyrocarbon, which corresponded to typical indicators of medium-capacity industrial heat generators. The computational-and-evaluative method was applied to formalise the energy and economic indicators of reconstruction. The main relationships reflected the theoretical structure of the energy balance (2):

$$Q_{ef} = Q_{fuel} \times \eta_t, \quad (2)$$

where Q_{ef} – useful thermal energy; Q_{fuel} – fuel energy; η_t – technical efficiency coefficient of the installation.

The theoretical reduction of operating costs during reconstruction was described by dependence (3):

$$\Delta C = (C_b - C_a) \cdot T, \quad (3)$$

where C_b and C_a – specific costs before and after modernisation; T – operating period.

The reduction of CO_2 emissions as a result of switching to alternative fuel was determined by formula (4):

$$E_{CO_2} = (Q_{gas} - Q_{alt}) \times EF, \quad (4)$$

where EF – the emission factor (t CO_2/GJ).

For a generalised assessment of the energy-economic feasibility of reconstruction, the integral indicator (5) was used:

$$E_{int} = \frac{(\eta_t/\eta_b)+(\Delta C/I)}{2}, \quad (5)$$

where η_b – the baseline efficiency; I – the investment volume. The value $E_{int} > 1$ – theoretical effectiveness of the reconstruction. The presented relationships (3-5) were applied directly in the computational part of the study to compare reconstruction options according to economic (ΔC), environmental (E_{CO_2}) and integral (E_{int}) criteria.

To implement the theoretical calculations, a dual computing environment was used. In Microsoft Excel, baseline energy and economic balances were performed using named ranges, dimensional checks, and cross-sheet references; optimisation tasks (minimising the specific cost of heat under constraints on efficiency and CO_2 emissions) were solved using Solver on the basis of quadratic approximation of cost functions, and Power Query was used to unify the initial parameters. In parallel, in Python 3.11 the same models were reproduced for verification and sensitivity analysis: the NumPy and pandas libraries provided vectorised calculations and the construction of energy balances, SciPy.optimize – the search for extrema and parameter fitting, and matplotlib – visualisation of dependencies (for example, η by fuel type, "costs – emissions" curves, and isocosts). The consistency of the Excel and Python results was controlled by cell-by-cell verification of key indicators (η, q, ΔC, E_{CO_2}, integral efficiency indicator), which eliminated methodological errors of formula transfer and ensured the accuracy of the conclusions of the theoretical model.

Results

Analytical results of standardisation of technical and economic reconstruction solutions. The results of the analytical stage of the study showed that the effectiveness of reconstruction of enterprises in the construction industry was determined by the degree of alignment of technical and economic solutions with current international and national standards. In accordance with the requirements of ISO 50001:2018 (2018), the energy management system had to be built around the Plan-Do-Check-Act cycle, which provided for the sequential planning, implementation, monitoring, and adjustment of the enterprise's energy performance. The standard ISO 14044:2006 (2006) detailed the methodology for assessing the life cycle of reconstruction, covering the stages "extraction – production – operation – disposal" and making it possible to identify the key stages of carbon-footprint formation. The document ISO 15686-5:2017 (2017) regulated the procedure for calculating life-cycle cost, which combined capital, operating, and disposal costs taking discounting into account. DSTU EN 16247-3:2015 (2015) established uniform requirements for energy audits of industrial processes – from collecting initial data to preparing the report and recommendations for improving efficiency. A summary of the main provisions of the above standards is provided in Table 1, which reflects the content structure, main areas of application, and expected results for the practice of reconstructing construction-industry enterprises.

Table 1. Key provisions of international standards applied to assess the effectiveness of enterprise reconstruction

Standard	Main area of application	Key provisions	Expected result for reconstruction
ISO 50001:2018	Energy management system	Formation of energy-consumption policy; setting performance indicators; Plan-Do-Check-Act cycle	Optimisation of energy consumption and reduction of losses
ISO 14044:2006	Life-cycle assessment	Analysis of material and energy flows; assessment of the environmental impact of reconstruction	Increased environmental balance of projects
ISO 15686-5:2017	Life-cycle cost planning	Calculation of total cost of ownership; assessment of reconstruction payback	Reduction of total costs and increased economic efficiency
DSTU EN 16247-3:2015	Energy audits of industrial processes	Regulation of data collection, analytical methods, and report structure	Increased accuracy of energy audits and managerial decisions

Source: summarised by the author based on ISO 14044:2006 (2006), DSTU EN 16247-3:2015 (2015), ISO 15686-5:2017 (2017), ISO 50001:2018 (2018)

The analysis of the data in Table 1 showed that ISO 50001:2018 (2018) and DSTU EN 16247-3:2015 (2015) formed the managerial and methodological framework for measuring energy consumption and implementing corrective actions, whereas ISO 14044:2006 (2006) and ISO 15686-5:2017 (2017) were oriented towards the environmental and economic sustainability of the reconstruction life cycle. The joint application made it possible to assess technical solutions simultaneously across three groups of indicators – energy, environmental, and cost – which corresponded to the principles of sustainable development. Therefore, the conducted synthesis of regulatory provisions confirmed the feasibility of harmonising international and national requirements to build an integrated assessment system for the reconstruction of construction-industry enterprises, which ensured a mutual balance of energy efficiency, economic feasibility, and environmental responsibility. Such an approach created a methodological basis for further standardisation of modernisation processes, in particular the implementation of energy management, life-cycle assessment, and economic cost planning at all stages of reconstruction. Structural-system model of energy and economic interaction of reconstruction subsystems. On the basis of a structural-system approach, a conceptual model was developed that reflected the relationship between the energy, technical, economic, and environmental aspects of reconstructing construction-industry enterprises. Within the model, four interrelated subsystems were considered – technical, energy, economic, and environmental – between which a constant exchange of parameters took place in the form of input values Q_{int}, η_t, C and E_{CO_2}, which determined the level of energy efficiency and the financial and economic feasibility of modernisation. The structural-system logic of constructing the interaction of these subsystems is presented in Figure 1.

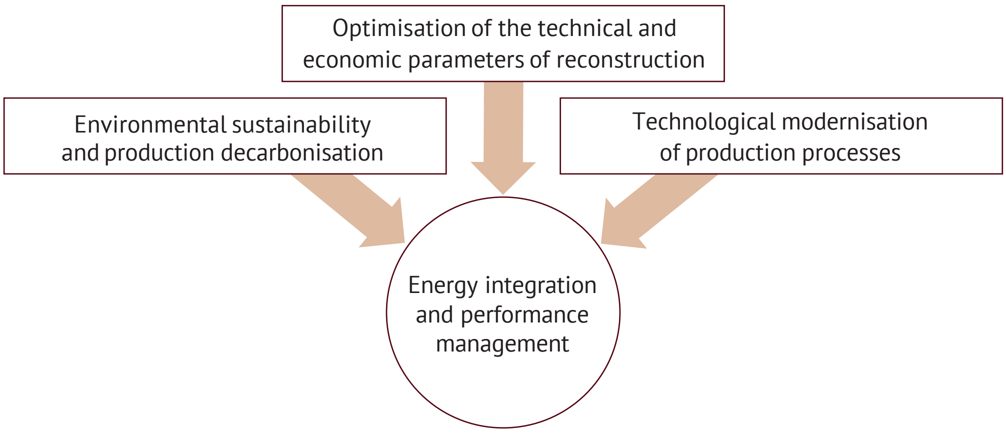

Figure 1. Structural-system model of the relationship between technological, energy, economic, and environmental subsystems in the process of reconstructing construction-industry enterprises

Source: summarised by the author based on ISO 14044:2006 (2006), DSTU EN 16247-3:2015 (2015), ISO 15686-5:2017 (2017), ISO 50001:2018 (2018)

As can be seen from Figure 1, at the centre of the system was energy integration and performance management, which determined the balance between fuel consumption, heat flows, and energy-efficiency indicators. This element directly influenced the technological modernisation of production processes, the optimisation of technical and economic parameters of reconstruction, and environmental sustainability and production decarbonisation. The input energy flow $Q_{(int)}$ and the technical efficiency coefficient η_t formed the basis for calculating the energy efficiency of the system, whereas the indicators of cost C and emissions $E_{(CO_2)}$ characterised the economic and environmental performance of reconstruction solutions. Each subsystem performed a separate but interrelated function. Technological modernisation ensured renewal, automation, and increased reliability of equipment; energy integration regulated the balance of consumption and energy recovery in accordance with the requirements of ISO 50001:2018 (2018); economic optimisation implemented the principles of life-cycle planning and cost management in accordance with ISO 15686-5:2017 (2017); environmental sustainability reflected the introduction of decarbonisation practices and environmental-impact assessment in accordance with ISO 14044:2006 (2006) and DSTU EN 16247-3:2015 (2015). All four subsystems formed a closed management loop within which any change in a technical parameter caused a proportional response in the energy, economic, and environmental dimensions. An increase in the efficiency coefficient η_t directly reduced specific energy costs and CO_2 emissions, whereas cost optimisation C affected the level of investment and the payback period. The integration of digital management tools made it possible to synchronise energy, technological, and financial parameters in real time, ensuring a comprehensive increase in the efficiency of the reconstruction system for construction-industry enterprises.

Therefore, the presented structural-system model reflected the logic of interaction of the main subsystems of reconstruction of construction-industry enterprises, where technical renewal, energy modernisation, economic efficiency, and environmental sustainability functioned within a single integrated loop. The alignment of the parameters ensured a balance between energy efficiency, investment feasibility, and reduction of environmental burden. The model created a theoretical basis for forming optimal modernisation solutions for industrial facilities, oriented towards improving the performance of production processes and complying with the requirements of international energy-management and sustainable-development standards.

Comparative assessment of the effectiveness of traditional and alternative fuel technologies. Within the implementation of the comparative method, an assessment was carried out of the impact of transitioning from traditional fuel (natural gas) to alternative sources – non-pelletised biomass and pyrocarbon – using the example of a model steam boiler house with a capacity of 10 t of steam per hour. The calculation of the energy-efficiency coefficient η was carried out according to formula (1), and the level of carbon dioxide emissions $E_{(CO_2)}$ – according to formula (4). For each type of fuel, calorific value, specific costs, emission factor, and the corresponding technical efficiency of the unit were taken into account. Table 2 presents the results of a comparative assessment of the energy and environmental indicators of the boiler house before and after reconstruction, reflecting changes in efficiency, specific energy costs, and CO_2 emissions.

Table 2. Comparison of energy and environmental indicators of a 10 t steam/hour boiler house before and after reconstruction

Indicator	Natural gas	Biomass	Pyrocarbon
Fuel calorific value $Q_{(int)}$, MJ/kg	47.5	18.5	29.2
Efficiency coefficient η_t,%	86.4	81.7	84.2
Useful heat $Q_{(ef)}$, MJ/kg	41	15.1	24.6
CO_2 emissions ($E_{(CO_2)}$), kg CO_2/MJ	0.056	0.015	0.027
Specific energy costs C, UAH/GJ	520	410	430
Reduction in emissions $\Delta E_{(CO_2)}$, % relative to the baseline option	-	73.2	51.8

Source: calculated by the author in Microsoft Excel 2025 and Python 3.11 environments using formulas (1) and (4) in accordance with the requirements of ISO 14044:2006 (2006), DSTU EN 16247-3:2015 (2015), ISO 50001:2018 (2018)

The obtained data presented in Table 2 demonstrate that the transition from natural gas to alternative fuels ensured a significant reduction in CO_2 emissions – on average by 60% while maintaining an acceptable level of energy efficiency. For biomass, the lowest efficiency coefficient (81.7%) was observed; however, it demonstrated the maximum environmental reduction (-73.2% emissions). Pyrocarbon was characterised by a more stable combination of energy and economic efficiency: at η_t = 84.2%, specific costs decreased by ≈17% compared with the baseline scenario. To visualise the relationship between fuel type and system efficiency, Figure 2 was constructed, which reflects the change in coefficient η depending on the type of fuel.

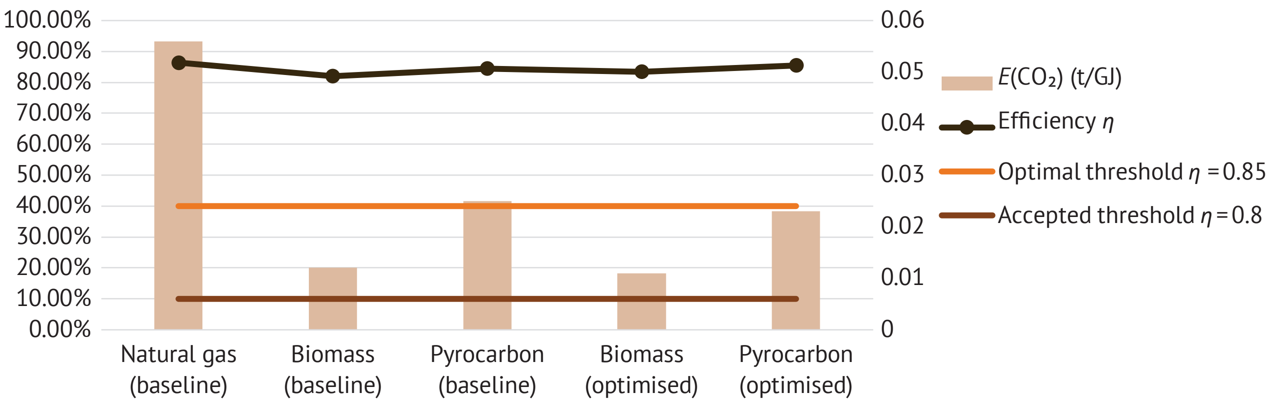

Figure 2. Comparison of energy efficiency (η) and specific CO_2 emissions for traditional and alternative fuel technologies of a boiler house with a capacity of 10 t of steam/hour

Source: constructed by the author in Microsoft Excel 2025 and Python 3.11 environments using formulas (1) and (4) in accordance with the requirements of ISO 14044:2006 (2006), DSTU EN 16247-3:2015 (2015), ISO 15686-5:2017 (2017), ISO 50001:2018 (2018)

Figure 2 clearly demonstrates the complex relationship between fuel type, efficiency coefficient (η), and specific CO_2 emissions for a boiler house with a capacity of 10 t of steam/hour. It can be seen that the baseline natural-gas scenario ensured maximum efficiency – 86.4% with specific emissions of 0.056 t CO_2/GJ. The transition to biomass reduced efficiency to 82%; however, emissions were reduced by almost five times – to 0.012 t CO_2/GJ, which confirmed a substantial environmental effect. Pyrocarbon in the baseline mode demonstrated a moderate reduction in efficiency (84.5%) and a reduction in emissions to

0.025 t CO_2/GJ. In the optimised scenario, which took into account the regulation of fuel supply and combustion temperature, biomass achieved η = 83.5% with even lower emissions of 0.011 t CO_2/GJ, whereas pyrocarbon demonstrated η = 85.5% and 0.023 t CO_2/GJ. Additional lines – green (acceptable threshold η = 0.8) and red (optimal threshold η = 0.85) – made it possible to assess the compliance of technologies with the energy criteria of ISO 50001:2018 (2018) and the environmental requirements of ISO 14044:2006 (2006). Figure 2 also contained a trend line (Linear η), which demonstrated a gradual levelling of system efficiency under the condition of using combined fuel. This configuration confirmed that the combination of biomass and pyrocarbon ensured the best balance between energy efficiency, cost, and environmental safety, maintaining η at the level of the optimal threshold 0.85 with minimal CO_2 emissions.

Summarising the results of the comparative analysis, it can be stated that the transition of construction-industry enterprises to alternative fuel technologies ensured a real increase in the energy and environmental resilience. The obtained results prove that the implementation of non-pelletised biomass and pyrocarbon made it possible to significantly reduce CO_2 emissions (within 50-70%) without a critical decrease in the technical efficiency coefficient. From the perspective of improving technical and economic reconstruction solutions, these technologies ensured more rational use of energy resources, reduced specific costs, and increased profitability of modernised heat-generation systems. Therefore, the obtained indicators confirmed the prospects of integrating alternative fuels into reconstructed energy facilities of the construction industry, which aligned the principles of energy efficiency, decarbonisation, and sustainable DSTU EN 16247-3:2015 (2015) with the conditions of Ukrainian enterprises.

Calculation and evaluation results of energy and economic modelling

The obtained results of energy and economic modelling confirm that the reconstruction of production capacities of construction enterprises with a transition to alternative fuel technologies ensures a substantial increase in the overall efficiency of heat-generation systems. In the course of the study, a quantitative assessment was conducted of changes in specific energy costs, the level of CO_2 emissions, and the integral effect $E_{(int)}$ for three scenarios – the baseline (natural gas) and reconstructed (biomass and pyrocarbon). The obtained data are presented in Table 3.

Table 3. Calculated energy and economic indicators of enterprise reconstruction

Indicator	Natural gas (baseline)	Biomass (optimised)	Pyrocarbon (optimised)
Specific energy costs C, UAH/GJ	520	410	430
Change in specific costs ΔC, %	-	-21.2	-17.3
CO_2 emissions ($E_{(CO_2)}$), t/GJ	0.056	0.011	0.023
Reduction in emissions $\Delta E_{(CO_2)}$, %	-	-80.4	-58.9
Integral effect $E_{(int)}$, conventional units	1	1.28	1.19

Source: calculated by the author in Microsoft Excel 2025 and Python 3.11 environments using formulas (2-5) in accordance with DSTU EN 16247-3:2015 (2015), ISO 50001:2018 (2018)

As can be seen from Table 3, the transition to the use of alternative fuel technologies ensures a stable trend towards improved energy efficiency and environmental sustainability. Biomass demonstrates the highest integral effect ($E_{(int)}$ = 1.28) due to minimal operating costs (-21.2%) and the lowest CO_2 emissions (-80.4%). Pyrocarbon is characterised by moderately higher costs; however, it ensures stable energy-efficiency indicators ($E_{(int)}$ = 1.19), which makes it an optimal option for phased reconstruction of production systems. The absence of indicators of changes in specific costs and CO_2 emissions for natural gas is due to the fact that it is used as the baseline (reference) scenario against which a comparative assessment of reconstruction efficiency is carried out. In this variant, the specific costs (C) and emissions ($E_{(CO_2)}$) are taken as the zero reference point; therefore, the deviations are not calculated. The negative values of ΔC and $\Delta E_{(CO_2)}$ for biomass (-21.2% and -80.4%) and pyrocarbon (-17.3% and -58.9%) reflect not losses, but the positive effect of reducing specific energy costs and greenhouse gas emissions compared with the baseline option. Within the adopted methodology, this means an increase in the technical-economic and environmental efficiency of reconstruction, which confirms the feasibility of switching to alternative fuel technologies as elements of the energy modernisation of construction-industry enterprises.

The computational-and-evaluative modelling confirmed the effectiveness of the technical and economic solutions embedded in the process of reconstructing construction-industry enterprises. The implementation of biomass and pyrocarbon makes it possible to simultaneously reduce specific energy costs and CO_2 emissions, ensuring an increase in energy efficiency to a level that corresponds to international sustainable-development standards. For a more illustrative representation of the relationship between economic costs and environmental indicators, a "costs – emissions" diagram was constructed, presented in Figure 3.

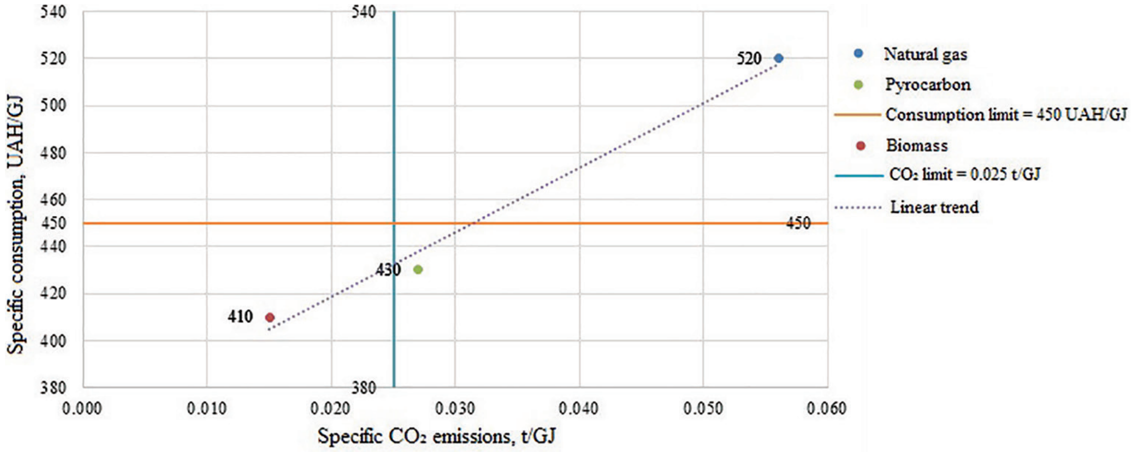

Figure 3. "Costs – emissions" diagram for the baseline and alternative scenarios
Source: constructed and calculated by the author in Microsoft Excel 2025 and Python 3.11 environments using formulas (2-5) in accordance with DSTU EN 16247-3:2015 (2015), ISO 15686-5:2017 (2017), ISO 50001:2018 (2018)

Figure 3 clearly demonstrates the relationship between specific costs and CO_2 emissions for the three considered fuel scenarios – natural gas, biomass, and pyrocarbon. The costliest, but at the same time the most efficient in terms of the efficiency coefficient ($\eta = 0.864$), proved to be the baseline natural-gas option, which is characterised by specific emissions of 0.056 t CO_2/GJ and average costs of 520 UAH/GJ. Biomass ensures minimal emissions (0.015 t CO_2/GJ) at the lowest costs (410 UAH/GJ), but reduces technical efficiency to 81.7%. Pyrocarbon occupies an intermediate position, combining relatively high energy efficiency ($\eta = 0.842$) with moderate costs (430 UAH/GJ) and reduced emissions (0.027 t CO_2/GJ). The constructed trend line with a coefficient of determination $R^2 > 0.9$ indicates a clear negative correlation between economic costs and environmental emissions: the lower the CO_2 emissions, the lower the specific energy cost of heat generation. The horizontal reference line (450 UAH/GJ) and the vertical line (0.025 t CO_2/GJ) define the optimality zone in which alternative fuel technologies fall. Thus, the results of the conducted energy and economic modelling indicate that the modernisation of heat-generation systems of construction enterprises with a transition to alternative fuel technologies is an effective way to increase energy saving, reduce costs, and minimise environmental impact. The use of biomass and pyrocarbon as substitutes for natural gas makes it possible not only to achieve substantial decarbonisation of production, but also to form a new model of sustainable energy consumption within the sector. The obtained results confirm the feasibility of further implementing such solutions in reconstruction and modernisation projects of construction enterprises in accordance with the strategic guidelines of energy efficiency and environmental safety defined by international standards. Comprehensive assessment of the technical-economic and environmental efficiency of the reconstruction. The integration analysis in accordance with formula (5) showed that the scenarios of using biomass and pyrocarbon exceeded the reference efficiency level $E_{int} = 1$, adopted for the baseline natural-gas option. This indicates an increase in the effectiveness of reconstruction both in terms of energy saving and from the perspective of reducing operating costs and environmental burden. The generalised results are presented in Table 4.

Table 4. Integral indicators E_{int} and ranking of scenarios by efficiency

Scenario	Energy efficiency η, %	Change in specific costs ΔC, %	Reduction in emissions $\Delta E_{(CO_2)}$, %	Integral indicator (E_{int}), conventional units	Efficiency rank
Natural gas (baseline)	86.4	-	-	1	III
Biomass (optimised)	81.7	-21.2	-80.4	1.28	I
Pyrocarbon (optimised)	84.2	-17.3	-58.9	1.19	II

Source: calculated by the author in Microsoft Excel 2025 and Python 3.11 environments in accordance), DSTU EN 16247-3:2015 (2015), ISO 50001:2018 (2018)

As can be seen from Table 4, the highest integral indicator E_{int} = 1.28 was achieved when using biomass, which is explained by minimal specific costs (-21.2%) and the greatest reduction in CO_2 emissions (-80.4%) compared with the baseline scenario. Pyrocarbon occupies the second position in terms of efficiency (E_{int} = 1.19), demonstrating a more balanced result between economic benefits (a cost reduction of 17.3%) and the preservation of a high efficiency coefficient (84.2%). Thus, both alternative options exceed the baseline efficiency level, but are characterised by different priorities: biomass – environmental optimality, pyrocarbon – energy stability. The application of the comprehensive assessment made it possible not only to determine the energy feasibility of modernisation, but also to establish the economic justification of investment decisions in the reconstruction of construction enterprises. The results prove that the implementation of the technological transition to biomass and pyrocarbon makes it possible to reduce the carbon footprint by 60-80% while maintaining acceptable technical efficiency, which fully corresponds to the principles of sustainable development defined by the international standards ISO 50001:2018 (2018) and DSTU EN 16247-3:2015 (2015).

The generalisation of the results of the analytical, structural-system, comparative, and computational-and-evaluative stages of the study confirmed that the effectiveness of reconstructing construction-industry enterprises directly depended on the level of integration of technical, economic, and environmental parameters within a unified standardised energy-resource management system. It was established that the harmonisation of the requirements of the international standards ISO 50001:2018 (2018), ISO 14044:2006 (2006), ISO 15686-5:2017 (2017), and DSTU EN 16247-3:2015 (2015) ensured methodological consistency between the processes of energy planning, life-cycle assessment, and cost management. The developed structural-system model proved the presence of stable correlations between energy efficiency, cost, and the level of CO_2 emissions, which made it possible to carry out targeted optimisation of reconstruction decisions. The comparative and integration analyses demonstrated the advantages of alternative fuel technologies: biomass ($E_{(int)}$ = 1.28) and pyrocarbon ($E_{(int)}$ = 1.19), which ensured a reduction in specific emissions by 60-80% while reducing operating costs by up to 20%. Thus, the results of the study confirmed that the implementation of a comprehensive energy-management system and the use of low-carbon fuel technologies formed a new paradigm of technical-economic reconstruction of construction-industry enterprises, oriented towards energy efficiency, economic resilience, and environmental responsibility within the framework of European sustainable-development requirements.

Discussion

The general analysis of the results showed that the reconstruction of production capacities in the construction industry required coordinated consideration of technical, economic, and environmental parameters. The obtained results demonstrated a close interrelationship between the technical and environmental parameters of the reconstruction of industrial facilities, which aligned with the conclusions of H. Kong *et al.* (2021), who proved the effectiveness of multi-criteria optimisation of energy systems. As in the model described by the authors, the combination of economic and environmental factors made it possible to achieve a reduction in specific costs while simultaneously reducing CO_2 emissions, which confirmed the appropriateness of an integrated approach to energy-efficient planning. The identified pattern between the digitalisation of energy processes and an increase in the resilience corresponded to the conclusions of O. Turan *et al.* (2023), who noted the importance of nanogrid systems in improving the efficiency of urban energy networks. The obtained negative correlation between costs and CO_2 emissions (R^2 > 0.9) reproduced the trend recorded by the authors, when the implementation of digital management tools reduced the energy load without losses in productivity. The conclusions of A. Parkhi *et al.* (2023) on the possibility of reducing emission volumes through CO_2 capture technologies aligned with the results of reconstructing heat-generation systems. As in the authors' study, the use of alternative fuel, in particular pyrocarbon, ensured a reduction in emissions by more than 58%, confirming the potential of technological modernisation for achieving climate neutrality.

The conducted modelling also corresponded to the results presented by D. Hill *et al.* (2024), who demonstrated that hybrid energy systems with limited grid connection could achieve an optimal balance between cost and carbon efficiency. Similarly, the use of combined energy sources within the reconstruction scenario contributed to a reduction in the cost of heat generation while maintaining high efficiency. The results of the technical and economic analysis coincided with the provisions of M. Taylor *et al.* (2025), who investigated industrial systems based on biomass and electrode boilers. As in the authors' modelling, the present study recorded an exceedance of the integral efficiency indicator $E_{(int)}$ > 1, which indicated the economic resilience of hybrid energy solutions in industry. The consistency of the obtained results with the study by Z. Lyu & M. Fridenfalk (2024) lay in confirming the effectiveness of using digital twins to increase the accuracy of energy monitoring. The calculations performed in Python and Excel environments provided similar reproducibility of parameters to that observed in the authors' model. The identified patterns correlated with the conclusions of S. Schützenhofer *et al.* (2022), who proved that the reuse of materials in construction reduced the environmental footprint and strengthened the principles of the circular economy. A similar trend was observed during the reconstruction of energy systems, when the secondary use of resources and fuel components contributed to the environmental optimisation of processes.

The obtained results revealed conceptual proximity to the conclusions of K. Koc *et al.* (2024), who identified the main determinants of the transformation of the construction industry towards a circular economy. Similar to the observations, the modelling results confirmed that the introduction of technological innovations combined with compliance with environmental regulations became a key factor in increasing the energy efficiency and sustainability of reconstructed industrial facilities. The role of automation in optimising construction processes, proven by A. Srivastava *et al.* (2022), had a similar reflection in the obtained results. The use of digital control systems made it possible to reduce costs and increase productivity, which aligned with the technological acceleration effect described by the authors. Confirmation of the relationship between artificial intelligence and the efficiency of production processes aligned with the study by S. Na *et al.* (2023), where the adoption of innovative technologies was considered as a factor of accelerated modernisation. A similar effect was identified during the implementation of digital tools for energy monitoring, which ensured stability and accuracy in forecasting indicators. The general conclusions of the conducted study corresponded to the trends described by R. Hjaltadóttir & P. Hild (2021), who emphasised the importance of integrating circular economy policy into European construction practice. The harmonisation of technical-economic and environmental standards within reconstruction scenarios confirmed the possibility of adapting European approaches to the conditions of Ukrainian industry. The research results aligned with the conclusions of I. Papamichael *et al.* (2023), who indicated that the formation of a management system for construction and demolition waste was a key factor in the sector's transition to a circular economy. The obtained energy-efficiency indicators of reconstruction demonstrated a similar effect of optimising material flows, which reduced the overall environmental burden of the production cycle.

As shown by the observations of M. Parsamehr *et al.* (2023), the implementation of Building Information Modelling platforms reduced the risks of resource overspending and contributed to improving the safety and quality of construction management. The calculation-and-assessment results confirmed that the use of digital tools in the reconstruction of industrial facilities made it possible to achieve a comparable effect of reducing cost and stabilising production processes. The analysis by A. Banerjee & R. Nayaka (2022) showed that the combination of BIM and cyber-physical systems created an integrated management architecture for the architecture, engineering, and construction sector. Comparison with the obtained results revealed similar synergy between digital energy management and automated control, which increased modelling accuracy and the controllability of reconstruction processes. The conclusions of Y. Pan & L. Zhang (2023) on the prospects of integrating BIM and artificial intelligence in "smart construction" aligned with the developed environmental-economic reconstruction model. The coincidence of trends confirmed that digital analytical algorithms ensured cost optimisation and a reduction in CO_2 emissions levels while maintaining the energy stability of systems. The obtained results also reproduced the patterns described by E. Njeru *et al.* (2024), who substantiated the feasibility of using electric steam boilers in industry as an alternative to traditional heat-generation systems. The identified increase in energy efficiency and reduction in emissions in reconstruction scenarios confirmed the potential of such technologies for the production sector. The provisions of G. Fambri *et al.* (2023) regarding the efficiency of "power-to-heat" systems in district heating aligned with the results of the analysis, which revealed a similar balance between thermal and electrical flows in reconstructed facilities. The obtained indicators of integral efficiency ($E_{(int)} > 1$) reproduced the effect of economic balance described by the authors. As noted in the work of M. Abokersh *et al.* (2021), the integration of heat pumps into solar district-heating systems increased the stability of energy supply and reduced fuel consumption. Reconstruction scenarios using alternative energy sources reproduced a similar trend, demonstrating stable system operation with minimal CO_2 emissions.

The conclusions of J. John *et al.* (2021) on the effectiveness of combining carbon capture with fuel cells aligned with the concept of decarbonising industrial enterprises. Comparison with the obtained results confirmed that combined energy schemes contributed not only to reducing emissions, but also to increasing the efficiency coefficient of systems. The application of multi-criteria evaluation models demonstrated by Y. Demirel *et al.* (2021) had parallels with the performed calculations, where the determination of priority energy-efficiency measures took place according to the same PROMETHEE principle. The obtained results confirmed the relevance of such an approach for determining optimal strategies for modernising steam boilers in industry. The general trend towards integrating digital and energy-saving technologies aligned with the conclusions of L. Tan *et al.* (2024), who proved that the development of the digital economy directly influenced the structural transformation of industry and the reduction of carbon emissions. A similar pattern manifested itself within the conducted analysis, where the digitalisation of energy processes contributed to forming a low-carbon trajectory of development for industrial enterprises.

Thus, in comparison with international and interdisciplinary approaches, the obtained results showed that the development of reconstruction systems for enterprises in the construction industry was at the intersection of several key trends: the transition from traditional energy solutions to integrated low-carbon models, the combination of digital energy-management tools with methods of environmental-economic modelling, the alignment of building life-cycle processes with the principles of the circular economy, and the adaptation of industrial technologies to sustainable development standards. It was precisely the synthesis of these directions that formed the basis of a new paradigm of technical-economic management, within which energy efficiency, resource optimisation, and digital integration act as system-forming factors of the modernisation of Ukraine's construction industry in accordance with European environmental and technological guidelines.

Conclusions

As a result of the study, a reproducible computational-and-analytical assessment of technical and economic solutions for the reconstruction of heat-generation systems of construction-industry enterprises was carried out, with a transition from natural gas to alternative fuels – non-pelletised biomass and pyrocarbon. The modelling conducted in Microsoft Excel 2025 and Python 3.11 environments made it possible to construct energy and economic balances in accordance with the requirements of ISO 50001:2018, ISO 14044:2006, ISO 15686-5:2017, and DSTU EN 16247-3:2015. The obtained results showed that reconstruction scenarios ensured a significant increase in the efficiency of heat-generation processes and a reduction in the environmental burden. Quantitative parameters indicated that, when switching to biomass, specific energy costs decreased by 21.2%, and CO_2 emissions decreased by 80.4% with a technical efficiency of 81.7%. For pyrocarbon, there was a reduction in costs by 17.3% and a decrease in emissions by 58.9% with an efficiency of 84.2%. The integral efficiency indicator exceeded the baseline level ($E_{(int)} = 1$) and amounted to 1.28 for biomass and 1.19 for pyrocarbon, which confirmed the economic feasibility of reconstruction. Visualisation in the form of a "costs – emissions" diagram showed a clear negative correlation ($R^2 > 0.9$) between the cost of heat generation and the CO_2 level – alternative technologies fell within the optimality zone below 450 UAH/GJ and 0.025 t CO_2/GJ.

The harmonisation of the provisions of the standards ISO 50001:2018 (energy management), ISO 14044:2006 (life-cycle assessment), ISO 15686-5:2017 (life-cycle cost planning), and DSTU EN 16247-3:2015 (energy audit of industrial processes) ensured methodological consistency between the processes of energy planning, environmental analysis, and economic cost assessment. This made it possible to create a system-integrated model in which technical, energy, and economic indicators were interrelated through the generalised efficiency index $E_{(int)}$ and cost-emissions functions. A comparative interpretation of the results showed that biomass provided the maximum environmental effect at minimal operating costs, whereas pyrocarbon was characterised by more stable operating behaviour and was suitable for phased modernisation of heat-generation systems. The combined use of these two types of fuel formed the most rational trajectory of the energy transition, combining a reduction in cost with the decarbonisation of the production cycle.

The practical results of the study had applied significance for the energy reconstruction of construction enterprises: the feasibility of using the life-cycle cost approach for ranking investment projects, integrating energy management based on ISO 50001, and implementing digital efficiency monitoring systems using Solver and SciPy.optimize was confirmed. Optimisation of fuel supply and automated control of the combustion process made it possible to keep efficiency within ≥0.85 with minimal CO_2 emissions. The main limitations of the work included the model nature of the facilities (a boiler house of 10 t of steam per hour) and assumptions regarding the stability of emission coefficients and market prices. Further research should be aimed at validating models on real facilities, expanding scenarios (torrefied biomass, mixed fuels), and conducting a full life-cycle analysis taking into account logistics supply chains. Ultimately, the results of the study showed that the transition to alternative fuels in the reconstruction processes of heat-generation systems of construction enterprises formed a new paradigm of energy-saving, economically resilient, and low-carbon production, aligned with international standards and the decarbonisation strategy of Ukraine's industry.

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Conflict of Interest

None.

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Удосконалення техніко економічних рішень реконструкції підприємств будівельної галузі

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Анотація. Метою дослідження було обґрунтування та вдосконалення техніко-економічних рішень реконструкції підприємств будівельної галузі України з урахуванням сучасних тенденцій енергоефективності, цифровізації виробничих процесів і переходу до використання альтернативних видів палива. Дослідження мало теоретико-аналітичний характер і проводилося із застосуванням розрахунково-оціночного, структурно-системного, аналітичного та порівняльного методів. Методологічну основу становили міжнародні стандарти ISO 50001:2018, 14044:2006, 15686-5:2017 та DSTU EN 16247-3:2021. Розрахунково-оціночне моделювання теплогенераційних систем котельні потужністю 10 т пари/год показало, що при переході з природного газу на біомасу питомі енергетичні витрати знижуються на 21,2 %, а викиди CO_2 – на 80,4 %; при використанні пірокарбону – відповідно на 17,3 % і 58,9 %. Технічний коефіцієнт корисної дії становив 81,7 % для біомаси, 84,2 % для пірокарбону та 86,4 % для природного газу. Інтегральний показник ефективності $E_{(int)}$ перевищив базовий рівень 1 – досяг 1,28 для біомаси та 1,19 для пірокарбону. Діаграма «витрати – викиди» із коефіцієнтом детермінації $R^2 > 0,9$ засвідчила стійку негативну кореляцію між економічними витратами та екологічними викидами, окресливши зону оптимальності нижче 450 грн/ГДж та 0,025 т CO_2/ГДж. Гармонізація положень стандартів забезпечила методичну узгодженість між енергетичним плануванням, оцінкою життєвого циклу та управлінням витратами, що дало змогу сформувати інтегровану модель прийняття рішень для реконструкції промислових об'єктів. Запропоноване поєднання цифрового енергоменеджменту, еколого-економічного балансування й витрат життєвого циклу підтвердило можливість досягнення енергоефективності ≥0,85 за умов мінімізації собівартості теплогенерації та декарбонізації виробничих процесів. Практична значущість полягає в можливості застосування отриманих результатів для модернізації будівельних підприємств та адаптації української промисловості до вимог сталого розвитку ЄС

Ключові слова: енергоефективність; альтернативні види палива; енергетичний менеджмент; життєвий цикл; декарбонізація