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Energy Sustainability of Construction Industry in Ukraine:
Awareness, Actions, and Barriers

Sostenibilidad Energética de la Industria de la Construcción en Ucrania:
Conciencia, Acciones y Barreras

Sustentabilidade Energética da Indústria da Construção na Ucrânia:
Consciência, Ações e Barreiras

Durabilité Énergétique de l'Industrie de la Construction en Ukraine :
Sensibilisation, Actions et Obstacles

Fuente: Autoría propia

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Abstract

The objective of the article is to assess how sustainable construction, grounded in Life Cycle Assessment (LCA) and Zero Carbon Footprint principles, can guide Ukraine's post-war reconstruction. Methodology: mixed-methods design combining a stakeholder survey and semi-structured interviews with an LCA of a representative public building using One Click LCA. Results: the case study achieves a 56.6% cut in annual energy use (1 214 000 ⊚ 527 150 kWh); district heating and stationary fuels dominate CO_2 (55.7% and 44.3%). Survey evidence shows limited LCA awareness and low practical uptake; key barriers are insufficient financial incentives and incomplete regulation. Discussion: we argue for alignment with EU standards, prioritizing thermal retrofits, heating-system modernization, professional training, and targeted incentives to accelerate adoption. Embedding LCA in energy management delivers environmental and economic co-benefits and strengthens infrastructure resilience. This study is based on a sample of n = 45 respondents, with a functional unit defined as the building's operational energy performance over 60 years.

Keywords: sustainable development, reconstruction, construction industry, environmental impact assessment

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Resumen

El objetivo del artículo es evaluar cómo la construcción sostenible, basada en los principios de Evaluación del Ciclo de Vida (LCA) y Huella de Carbono Cero, puede guiar la reconstrucción posbélica de Ucrania. Metodología: diseño de métodos mixtos combinando una encuesta a partes interesadas y entrevistas semiestructuradas con un LCA de un edificio público representativo utilizando One Click LCA. Resultados: el estudio de caso logra una reducción del 56,6% en el consumo anual de energía (1 214 000 ⊚ 527 150 kWh); la calefacción urbana y los combustibles estacionarios dominan las emisiones de CO_2 (55,7% y 44,3%). La encuesta muestra un conocimiento limitado del LCA y una baja adopción práctica; las principales barreras son la insuficiencia de incentivos financieros y la regulación incompleta. Discusión: se argumenta la necesidad de alineación con las normas de la UE, priorizando la rehabilitación térmica, la modernización de los sistemas de calefacción, la formación profesional y los incentivos específicos para acelerar la adopción. La integración del LCA en la gestión energética genera beneficios ambientales y económicos, fortaleciendo la resiliencia de la infraestructura. Este estudio se basa en una muestra de 45 participantes, con una unidad funcional definida como el desempeño energético operativo del edificio a lo largo de 60 años.

Palabras clave: desarrollo sostenible, reconstrucción, industria de la construcción y evaluación del impacto ambiental

Résumé

L'objectif de cet article est d'évaluer comment la construction durable, fondée sur les principes d'Évaluation du Cycle de Vie (LCA) et de l'Empreinte Carbone Zéro, peut guider la reconstruction post-guerre de l'Ukraine. Méthodologie : conception à méthodes mixtes combinant une enquête auprès des parties prenantes et des entretiens semi-structurés avec un LCA d'un bâtiment public représentatif utilisant One Click LCA. Résultats : l'étude de cas atteint une réduction de 56,6 % de la consommation énergétique annuelle (1 214 000 ⊚ 527 150 kWh) ; le chauffage urbain et les combustibles stationnaires dominent les émissions de CO_2 (55,7 % et 44,3 %). Les enquêtes montrent une faible connaissance du LCA et une adoption pratique limitée ; les principales barrières sont l'insuffisance des incitations financières et une réglementation incomplète. Discussion : il est nécessaire de s'aligner sur les normes de l'UE, en priorisant la rénovation thermique, la modernisation des systèmes de chauffage, la formation professionnelle et les incitations ciblées pour accélérer l'adoption. L'intégration du LCA dans la gestion énergétique apporte des co-bénéfices environnementaux et économiques et renforce la résilience des infrastructures. Cette étude s'appuie sur un échantillon de n = 45 participants, l'unité fonctionnelle étant définie comme la performance énergétique opérationnelle du bâtiment sur 60 ans.

Resumo

O objetivo do artigo é avaliar como a construção sustentável, fundamentada nos princípios de Avaliação do Ciclo de Vida (LCA) e Pegada de Carbono Zero, pode orientar a reconstrução pós-guerra na Ucrânia. Metodologia: desenho de métodos mistos combinando um inquérito a partes interessadas e entrevistas semiestruturadas com um LCA de um edifício público representativo utilizando One Click LCA. Resultados: o estudo de caso alcança uma redução de 56,6% no consumo anual de energia (1 214 000 ⊚ 527 150 kWh); o aquecimento urbano e os combustíveis estacionários dominam as emissões de CO_2 (55,7% e 44,3%). O inquérito revela conhecimento limitado sobre LCA e baixa adoção prática; as principais barreiras são incentivos financeiros insuficientes e regulamentação incompleta. Discussão: defende-se a necessidade de alinhamento com normas da UE, priorizando retrofits térmicos, modernização de sistemas de aquecimento, formação profissional e incentivos direcionados para acelerar a adoção. A incorporação do LCA na gestão energética gera co-benefícios ambientais e económicos, fortalecendo a resiliência da infraestrutura. Este estudo baseia-se numa amostra de n = 45 participantes, com a unidade funcional definida como o desempenho energético operacional do edifício ao longo de 60 anos.

Palavras-chave: desenvolvimento sustentável, reconstrução, indústria da construção e avaliação de impacto ambiental

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Energy Sustainability of Construction Industry in Ukraine:
Awareness, Actions, and Barriers

Mots-clés : Développement Durable, Reconstruction, Industrie de la Construction et Évaluation de l'Impact Environnemental

Introduction

The construction industry plays a pivotal role in national economic stability and quality of life. However, it is also a major driver of environmental degradation due to carbon emissions, resource use, and waste (Firmansyah et al., 2024; Xue et al., 2024). To mitigate these impacts, green building has emerged as a key strategy (Cong, 2024; Liu et al., 2024; Wu & Ying, 2024). Green building emphasizes lowering emissions, improving energy efficiency, and stewarding resources across the building life cycle—from design and construction to operation and end-of-life (Berardi, 2013)[1].

The objective of the article is to assess how sustainable construction, grounded in Life Cycle Assessment (LCA) and Zero Carbon Footprint principles, can guide Ukraine's post-war reconstruction

In the context of Ukraine, the necessity for green building practices has become increasingly urgent due to the widespread destruction caused by the ongoing war. As of January 2024, the estimated direct damage to Ukraine's infrastructure amounts to hundreds of billions of USD, encompassing extensive losses across residential buildings, industrial facilities, energy infrastructure, and essential public services such as education and healthcare[2]. This large-scale devastation highlights the pressing need for a comprehensive and sustainable reconstruction strategy that aligns with European Union (EU) standards, particularly those concerning Life Cycle Assessment (LCA) and Zero Carbon Footprint principles (Pomponi & Moncaster, 2016; Bruce-Hyrkäs, Pasanen, & Castro, 2018; Zabalza Bribián, Aranda Usón, & Scarpellini, 2009).

The reconstruction of Ukraine's infrastructure presents a unique opportunity to integrate advanced green building practices and standards. These standards are not only vital for environmental sustainability but also essential for ensuring resilience against future conflicts and the looming threat of climate change. Key areas of focus include the construction of high-quality bomb shelters, underground schools, and other resilient infrastructures designed to withstand potential future threats while providing safe and sustainable environments for the population (Liu & Mi, 2017). The EU's green building standards (Congedo, Baglivo, D'Agostino, & Albanese, 2024; De Wolf, Cordella, Dodd, Byers, & Donatello, 2023; Maduta, D'Agostino, Tsemekidi-Tzeiranaki, Castellazzi, Melica, & Bertoldi, 2023; Vela Almeida et al., 2023), particularly the integration of LCA principles, are central to this effort. LCA involves a comprehensive evaluation of the environmental impacts of a building throughout its entire lifecycle, helping to minimize resource use, reduce waste, and lower carbon emissions (Zabalza Bribián, Aranda Usón, & Scarpellini, 2009). Additionally, the Zero Carbon Footprint principle strives to balance the amount of carbon emitted with an equivalent amount sequestered or offset, aiming for net-zero carbon emissions (Congedo et al., 2024; De Wolf et al., 2023).

Implementing these standards in Ukraine's reconstruction efforts will not only enhance environmental sustainability but also promote economic efficiency and long-term resilience. However, several barriers hinder the widespread adoption of green building practices in Ukraine. These

[1] "End-of-life" includes deconstruction, waste processing, and disposal; embodied-carbon accounting follows the system boundaries described in Methods.

[2] Authors' compilation of public assessments as of January 2024 (current USD); scope includes direct, documented infrastructure damages, including the Kakhovka HPP impact.

include a lack of awareness among stakeholders, insufficient financial incentives, and regulatory challenges (Abdulai et al., 2024; Ohene et al., 2023; Zhan et al., 2023). Overcoming these barriers requires coordinated efforts from policymakers, the construction industry, and international organizations. Critical steps include increasing awareness, providing financial incentives, and aligning local regulations with EU standards.

This study aims to assess the current state of green building practices in Ukraine, with a focus on the awareness, actions, and barriers related to their implementation. Additionally, it evaluates the impact of the ongoing conflict on the construction industry and underscores the necessity of integrating green building standards into the reconstruction process. By highlighting the importance of sustainable practices, this research seeks to contribute to the broader efforts of rebuilding Ukraine in a manner that ensures environmental sustainability, economic efficiency, and resilience against future challenges (Galimova, Ram, & Breyer, 2022; Lund & Mathiesen, 2009).

Furthermore, this study aligns with the broader objectives of the European Union's sustainable development agenda. The integration of green building standards in Ukraine's reconstruction efforts will contribute to the EU's goals of achieving climate neutrality in the building stock by 2050 and reducing dependency on Russian fossil fuels before 2030, as outlined in initiatives like the Renovation Wave (Maia, Harringer, & Kranzl, 2023; Shcherbyna, 2022; Maia et al., 2023; Tzani et al., 2023) and the revised Energy Performance of Buildings Directive. The uptake of digital and smart solutions in building design, along with improvements in energy flexibility and circular construction approaches, will also be instrumental in advancing these objectives. Ultimately, the adoption of these practices will play a crucial role in enhancing the energy efficiency, resilience, and sustainability of Ukraine's rebuilt infrastructure, setting a precedent for other nations facing similar challenges.

Materials and Methods

Scope of the Study

The insights from this study offer valuable guidance for post-conflict reconstruction planning, particularly in regions recovering from prolonged warfare or experiencing temporary ceasefires. According to publicly available conflict monitoring reports, over 20 armed conflicts remain active globally, with most exerting substantial socioeconomic disruption. The Ukrainian case, addressed herein, exemplifies broader challenges related to energy-resilient construction. These findings are relevant to contexts where large-scale internal displacement necessitates rapid housing provision, alongside urgent improvements in building energy performance.

Study Design and Scope

The analysis drew upon both primary and secondary sources. The study involved 45 respondents, including representatives of government agencies, engineers, construction contractors, architects, and representatives of international humanitarian organisations. A non-probability sample (convenience sample) was used to recruit participants, which made it possible to include experts with relevant experience and availability. Interviews comprised open-ended items designed to evaluate stakeholder familiarity with sustainable construction principles, while surveys employed Likert-type scales to measure perceptions of implementation challenges and perceived advantages. The design of data collection adhered to established protocols ensuring validity and representativeness. Qualitative responses were coded thematically, while quantitative data were processed using appropriate statistical techniques to ensure analytical robustness.

Secondary information was compiled from scholarly literature, policy documents, technical guidelines, and international standards related to sustainable construction, with particular reference to LCA and carbon neutrality. These materials offered critical insights into Ukraine's regulatory landscape, economic constraints, and the operational status of its construction sector. Recognized frameworks such as ISO 14040 and ISO 14044 were employed to guide the life cycle assessment component of the study (Bruce-Hyrkäs, Pasanen, & Castro, 2018).

Life Cycle Assessment (LCA) Methodology

In the context of the built environment, LCA provides quantifiable data on the environmental performance of construction materials, methods, and entire building systems. By converting these impacts into measurable indicators—such as carbon footprint, energy demand, water use, and waste generation—LCA informs choices that reduce environmental burdens across the entire life cycle of buildings.

According to international guidelines (EN ISO 14040 and 14044), the assessment includes a minimum of 16 stages, grouped into production (A1–A3), construction (A4–A5), use (B1–B7), and end-of-life (C1–C4) phases. The core modules A1–A3 are mandatory and include raw material supply, transportation to the manufacturing facility, and product manufacturing. This standardized structure ensures comparability across studies and supports compliance with environmental certification systems.

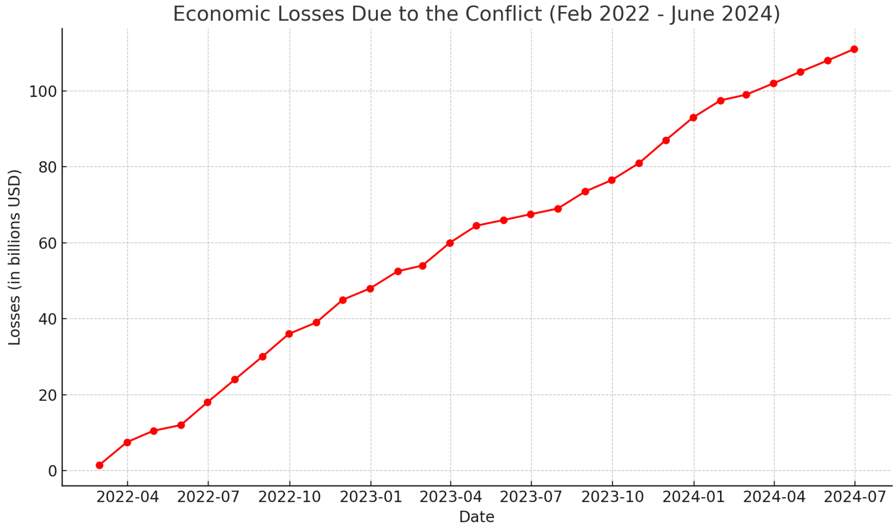

Figure 1. Economic Losses Due to the Conflict: This line graph illustrates the timeline and extent of economic losses from the beginning of the conflict in February 2022 to June 2024

Source: Author's own elaboration based on research data.

The study employed the Life Cycle Assessment (LCA) methodology according to ISO 14040/14044 and was performed at the building level. The functional unit is defined as the provision of a comfortable internal climate (heating, cooling, lighting, and ventilation) for a single educational building over an assumed service life of 60 years. System boundaries include Modules A1–A3 (Product Stage: material extraction, transport, manufacturing), Module B6 (Operational Energy Use, per EN 15978), and Module C3/C4 (End-of-Life: demolition, waste treatment, and disposal). The analysis is based on a hybrid approach. Emission factors for energy consumption and regional grid mixes were sourced from the Ecoinvent 3.7 database and verified with local energy provider reports. No new primary modeling was required for the baseline assessment.

In this study, LCA was applied to assess and compare the environmental impact of traditional versus green construction practices in the Ukrainian post-war reconstruction context. The assessment was performed using One Click LCA, a robust and internationally recognized software platform tailored for the construction sector. The tool supports the quantification of environmental indicators in alignment with European standards, making it particularly suitable for evaluating energy resilience and sustainability under war recovery conditions.

The One Click LCA license was provided through the Erasmus+ project "Support for higher education systems in a context of climate change mitigation through regional-level carbon footprint caused by a product, building and organization," which enabled access to extended datasets and scenario modeling. Additional comparative insights were drawn using other LCA platforms, such as SimaPro, GaBi, and OpenLCA, to ensure methodological robustness and alignment with best practices.

This methodology enables replication and scalability, offering a consistent framework for researchers and practitioners across various geopolitical contexts. It provides critical insights for policy formulation, infrastructure planning, and climate adaptation strategies. Future work may focus on expanding the scope of LCA in post-war reconstruction by integrating social and economic parameters and exploring its application across broader geographic regions and typologies.

Limitations

A detailed breakdown of post-intervention CO_2 factors is beyond the defined functional unit and system boundaries; to preserve protocol consistency, we restrict the manuscript to numerical consistency checks.

Results

Impact of the War on Ukraine's Infrastructure

The war in Ukraine has caused extensive destruction across national infrastructure, resulting in severe economic losses and necessitating an urgent, coordinated reconstruction approach. By January 2024, total direct damages were estimated to be on the order of hundreds of billions of USD, including substantial impacts from the Kakhovka hydroelectric plant explosion.

Residential infrastructure has been disproportionately affected, with over 250 000 dwellings damaged or destroyed about 222 000 private houses, over 27 000 apartment buildings, and about 526 dormitories. The resulting losses are estimated at ≈ \$59 billion (current USD), ≈ \$5 billion higher than late 2023 figures.

Damage to public and private infrastructure sectors is estimated at $36.8 billion. Industrial and commercial facilities suffered $13.1 billion in losses, reflecting the destruction of 78 private enterprises and 348 state-owned entities. Energy infrastructure, essential for national operations, incurred approximately $9 billion in damages, while agricultural losses reached $8.7 billion. The housing and utilities sector reported damages of $4.5 billion, and healthcare facilities $3.1 billion[3].

These assessments underline the need for a resilient reconstruction strategy that not only restores affected infrastructure but also integrates modern, durable construction techniques in compliance with international standards. Figure 1 presents a timeline of economic losses from February 2022 through June 2024.

The devastation has made it clear that any reconstruction efforts must incorporate advanced methodologies, such as Life Cycle Assessment (LCA) and Zero Carbon Footprint principles, to ensure long-term sustainability and resilience against potential future conflicts.

Results from the structured interviews and surveys highlighted varying levels of awareness regarding green building practices. Approximately 45% of respondents were familiar with Life Cycle Assessment (LCA) methodologies, but only 25% had practical experience applying them. Barriers identified include a lack of financial incentives and insufficient regulatory frameworks. The evidence points to a pressing requirement for improved education and policy adjustments to advance the integration of sustainable practices throughout Ukraine.

Environmental Consequences

The environmental consequences of the ongoing conflict in Ukraine are profound, particularly in the context of the extensive destruction of buildings and infrastructure. One of the most immediate environmental impacts arises from the demolition and destruction of buildings, which releases vast amounts of debris, dust, and hazardous materials into the environment. The collapse of concrete structures, for example, contributes to the dispersion of particulate matter and other pollutants, which can have both immediate and long-term effects on air quality. Furthermore, the rubble generated from the destruction has overwhelmed waste management systems, leading to improper disposal practices that exacerbate environmental degradation.

The damage to infrastructure, particularly in urban areas, has also had severe environmental repercussions. The destruction of roads, bridges, and railways has disrupted the transportation of goods and services, leading to increased emissions from vehicles forced to take longer routes. Moreover, the collapse of water supply and sewage systems has resulted in the contamination of water bodies with untreated sewage, chemicals, and debris, posing significant risks to public health and aquatic ecosystems.

Additionally, the energy infrastructure in Ukraine has suffered extensive damage, further compounding environmental issues. Damage to power plants and energy networks has necessitated the use of less efficient and more polluting energy sources, contributing to higher greenhouse gas emissions. Interruptions in energy supply have further impeded initiatives to mitigate the environmental consequences of the war, as numerous regions face challenges in sustaining fundamental environmental protection measures without stable electricity.

The combined effects of these environmental consequences have created a situation where the rebuilding of Ukraine's infrastructure must not only address the physical reconstruction of buildings and infrastructure but also incorporate strategies for environmental remediation and sustainable development. This includes the proper management of construction waste, the decontamination of polluted sites, and the rebuilding of energy-efficient and environmentally friendly infrastructure. Implementing such measures is essential to guarantee that reconstruction activities mitigate, rather than amplify, the environmental damage caused by the war, while promoting a sustainable and resilient trajectory for Ukraine's future.

Resilience and Sustainability of Reconstructed Infrastructure

Green building approaches have become central to reducing the environmental footprint of the construction sector. These approaches target improvements in energy efficiency, carbon emission reduction, and sustainable resource management across a building's full life cycle, including site selection, design, construction, operation, maintenance, and decommissioning. By following these principles, buildings are designed to be environmentally responsible and resource efficient. Life Cycle Assessment (LCA) provides a critical framework for evaluating environmental impacts at each stage of a building's existence—from raw material extraction to demolition—facilitating identification of opportunities to enhance environmental performance and reduce resource use. The

[3] Estimates reflect the authors' synthesis of publicly reported government, international-organization, and sectoral assessments as of January 2024 (current USD), including impacts from the 6 June 2023 Kakhovka HPP destruction. Scope: direct, documented infrastructure damages only. Method: de-duplication and harmonization across overlapping reports; figures are rounded (nearest 0.1 bn) and may vary due to reporting lags and revisions. Currency: USD at contemporaneous rates; no PPP adjustment. Categories: residential, infrastructure, industry/commercial, energy, agriculture, housing/utilities, and healthcare; dwelling counts include private houses, apartment blocks, and dormitories. Uncertainty: ± a few percent; subsequent updates may differ.

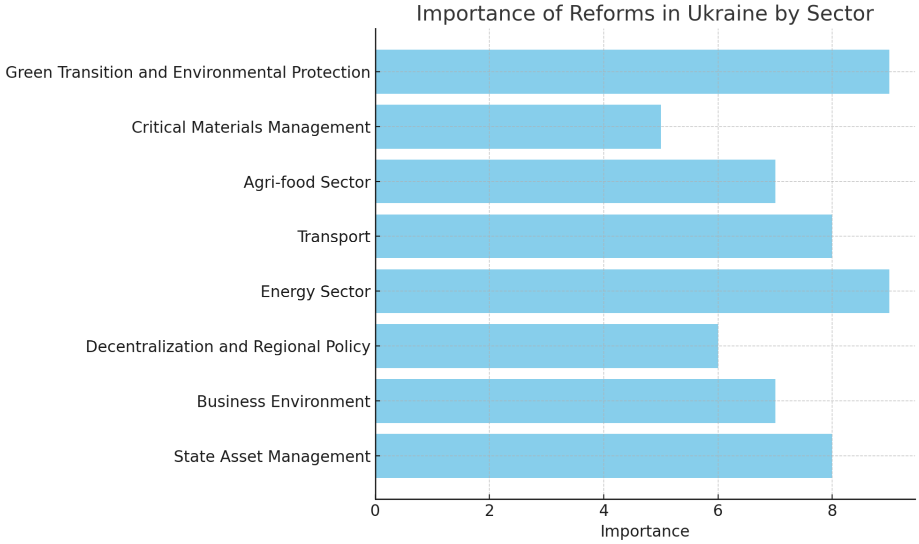

Figure 2. Importance of Reforms in Ukraine by Sector: This bar chart shows the importance of reforms in various sectors, highlighting the critical areas for sustainable reconstruction, scale from 1 (minimum) to 8 (maximum)

Source: Author's own elaboration based on research data.

Zero Carbon Footprint concept further aims to achieve net-zero emissions by balancing carbon output with equivalent sequestration or offsets.

Despite global progress in green construction, Ukraine faces significant obstacles in implementing these standards, particularly given the ongoing war and its widespread damage to infrastructure. Reconstruction efforts present a unique chance to integrate advanced green building practices, which are essential not only for environmental sustainability but also for enhancing resilience against future conflicts and climate change. Priority initiatives include constructing durable bomb shelters, underground schools, and other resilient facilities capable of withstanding potential threats while ensuring safe and sustainable conditions for inhabitants. Nevertheless, adoption of green building practices remains constrained by limited stakeholder awareness, insufficient financial incentives, and regulatory barriers, necessitating coordinated action by government bodies, international organizations, and the private sector.

The bar chart in Figure 2 illustrates the importance of various reforms in Ukraine, with each sector rated on a scale from 1 (minimum) to 8 (maximum), where 1 represents the minimum importance and 8 represents the maximum importance. This visual representation helps to identify the critical areas that require attention for sustainable reconstruction, based on the perceived significance of reforms within each sector. The importance of the reforms in Figure 2 was based on expert evaluations or stakeholder surveys using a ranking method, commonly applied in similar research contexts. One common approach is the use of Likert scales or importance rating scales, where participants rate different reforms based on their perceived significance. For instance, a method might ask participants to rank reforms on a scale of 1 to 8, with 1 indicating minimal importance and 8 indicating the highest importance. Such methods are effective in gathering structured qualitative data from stakeholders, ensuring that each reform is evaluated based on predefined criteria.

The sustainability challenges faced by Ukraine's construction sector are intensified by rapid population growth, accelerating urbanization, and the rising demand for housing and infrastructure, which collectively exert substantial pressure on natural resources and the environment. Despite these pressing issues, research addressing the level of awareness, implementation practices, and barriers to sustainable construction in Ukraine remains limited. This study seeks to fill this knowledge gap by examining the current state of sustainability in the construction industry and highlighting areas in need of improvement.

Insights can be drawn from successful post-war reconstruction experiences in regions such as the Balkans and Rwanda, where sustainable practices were embedded at the onset of rebuilding initiatives. These cases illustrate that sustainable reconstruction not only fulfills immediate recovery needs but also strengthens long-term stability and socio-economic development. Applying such lessons in the Ukrainian context can guide the formulation of effective strategies for rebuilding infrastructure in a manner that is both sustainable and resilient.

The role of the government is crucial in promoting green building practices. Updating regulatory frameworks and policies to support the adoption of sustainable construction methods is essential. This includes setting clear guidelines and providing financial incentives for green building projects. Government intervention can play a significant role in raising awareness, providing necessary training, and ensuring compliance with international standards.

By integrating EU standards such as LCA and Zero Carbon Footprint principles, Ukraine can rebuild its infrastructure in a manner that ensures environmental sustainability, economic efficiency, and resilience against future challenges. Overcoming the barriers to green building adoption will require coordinated efforts from all stakeholders, including policymakers, builders, and international organizations.

Optimizing Sustainable Reconstruction: Insights from Life Cycle Assessment (LCA)

For the One Click LCA calculation, a three-storey building with a total area of 47 894 m² and a volume of 168 721 m³ was used. The building has central heating, electricity from the regional grid, and centralized water supply and sewerage. It is important to note that the building has an unheated attic and a warm basement. Such buildings are typical for many cities in Ukraine.

The optimization process focused on several key areas, including enhancing energy efficiency through building insulation, upgrading heating systems, and implementing renewable energy technologies. These measures were evaluated using LCA to assess their impact on reducing greenhouse gas emissions and improving overall energy consumption. By systematically applying these optimizations, the operational energy use was reduced by approximately 56.6%, demonstrating the effectiveness of integrated sustainability measures.

An analysis of the building's thermal performance showed that the thermal resistance of the exterior walls, attic ceiling and basement floor did not meet regulatory requirements, leading to significant heat losses. The energy audit found that the main sources of energy consumption are as follows:

- Space heating: 513 329 kWh/year, accounting for 84.15% of the building's total energy consumption.
- Lighting: 76 518 kWh/year, or 12.55% of total consumption.
- Other consumers: 20 153 kWh/year, or 3.30% of total consumption.

Table 1 provides information on the main sources and energy consumption, it reports audit subtotals, not the full building baseline. Totals may not sum to 100% due to rounding.

Energy Source	Energy Consumption (kWh/year)	%
Space heating	513,329	84.15
Lighting	76,518	12.55
Other consumers	20,153	3.30
Subtotal	610,000	100.00

Table 1.Main categories of energy consumption (audit subtotal).

The building's baseline annual energy consumption prior to implementing energy efficiency measures was 1 214 000 kWh, representing a substantial load for a facility of this type[4]. This highlights the necessity for modernization aimed at lowering energy use and enhancing indoor environmental conditions.

The analysis led to the proposal of several measures aimed at enhancing the building's energy efficiency, including:

1. Insulation of the attic ceiling: This will significantly reduce heat loss through the roof, which is one of the largest areas of loss in old buildings.
2. Replacement of windows: The existing wooden windows with glass do not meet modern energy efficiency requirements, which leads to significant heat loss through air infiltration.
3. Installation of an individual heating point (IHP): This will allow you to more accurately regulate the heat supply to the building depending on the external temperature conditions and the needs of the premises.
4. Installation of thermostats on radiators: This will allow you to regulate the temperature in each room individually, reducing overheating and, accordingly, excessive energy consumption.
5. Installation of automatic balancing valves: They will ensure an even distribution of heat throughout the heating system, which will reduce the risk of localised overheating or underheating.

Following the implementation of these measures, the building's total annual energy consumption would decrease to 527 150 kWh, representing a 56.6% reduction. This is a significant achievement, which demonstrates the

[4] From the building energy audit and thermal survey; baseline is pre-retrofit metered/estimated annual use. Envelope U-values for walls, attic ceiling, and basement floor do not meet regulatory minima, driving heat losses.

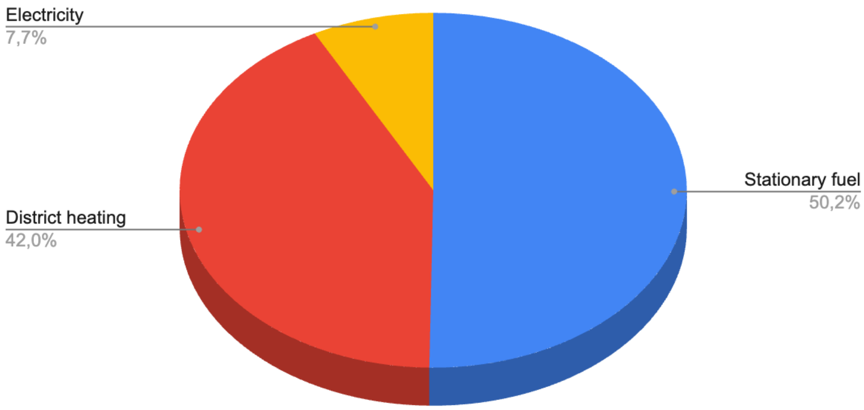

Figure 3. Energy consumption breakdown of a building by resource type: Results of a life cycle assessment using One Click LCA

Source: Author's own elaboration based on research data.

effectiveness of the measures taken. In particular, the insulation of the attic ceiling and the installation of an IHP will have the greatest impact, reducing heat loss through the roof and optimising heat transfer to the building.

The estimated CO_2 emission reduction was 1 115 tonnes per year, making this project not only economically viable but also environmentally important for the region.

Energy Source	Energy Consumption (kWh/year)	%
Stationary fuel	610,000	50.25
Electricity	94,000	7.75
District heating	510,000	42.00
Subtotal	1,214,000	100.00

Table 2. Energy consumption breakdown of a building by resource type.

Life Cycle Assessment (LCA) serves as a vital methodology for evaluating building energy performance, enabling a comprehensive analysis of energy consumption and related greenhouse gas emissions across all life cycle stages. In this study, the building's energy cycle was assessed using One Click LCA software, accounting for stationary and mobile fuel use, electricity, and district heating consumption.

Figure 3 illustrates that the building's total energy consumption amounts to 1 214 000 kWh, with 610 000 kWh (50.25%) derived from stationary fuel, primarily natural gas. Electricity accounts for 94 000 kWh/year (7.75%) of total consumption and is used for lighting, office equipment, and other electrical equipment; mobile fuel consumption is only 4.7 kWh/year, which is insignificant and indicates limited use of mobile energy sources for building maintenance. A significant share, namely 510 000 kWh (42.00%), is accounted for by district heating, which is used to maintain the temperature regime in the cold season.

Table 2 provides information on the building's energy consumption by resource type. Totals may not sum to 100% due to rounding.

The analysis of energy consumption by type of resource showed that half of the energy is used in the form of natural gas, which provides heating and hot water for the building. District heating accounts for 42.00% and electricity for 7.75% of the total energy consumption.

These findings emphasize the need to optimise energy use, particularly regarding stationary fuel consumption and district heating systems. Building insulation and modernisation of heating systems, including the installation of individual heating points and thermostats, can significantly reduce energy costs. Improving the efficiency of electricity use, for example through the introduction of energy-efficient lighting systems and automation, can also contribute to an overall reduction in energy consumption. This, in turn, will not only reduce energy costs, but also reduce greenhouse gas emissions, which is important for achieving sustainable development goals.

The life cycle assessment of the building using One Click LCA allowed us to analyse in detail the distribution of energy consumption and identify key areas for improving energy efficiency. The results highlight the need to modernise the building's energy system, including optimising the use of natural gas and district heating,

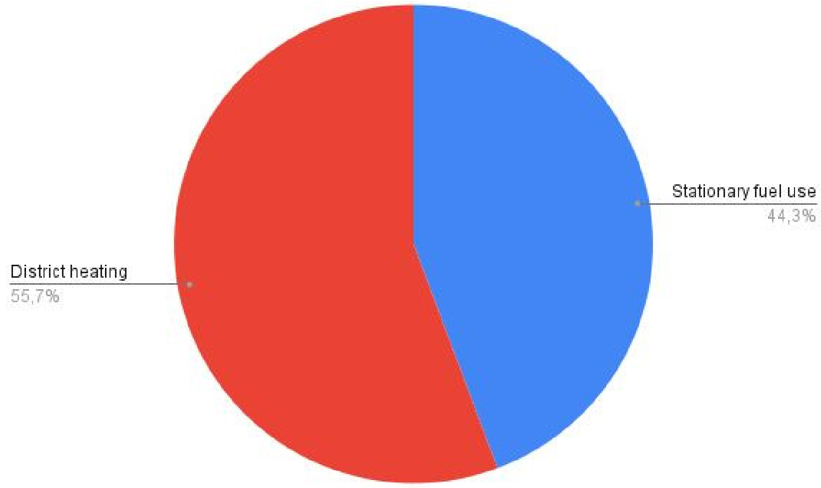

Figure 4. Distribution of CO_2e emissions by energy use categories: Results of global warming assessment using One Click LCA

Source: Author's own elaboration based on research data.

as well as introducing modern technologies to improve the efficiency of electricity use. This study illustrates that incorporating LCA into energy management can yield substantial environmental and economic gains by lowering buildings' carbon footprint and enhancing overall sustainability.

The calculations performed by One Click LCA on Figure 4 demonstrate the distribution of greenhouse gas (GHG) emissions in the building based on different categories of energy use.

The largest contribution to global warming comes from district heating, accounting for 55.7% of total CO_2e emissions. The second largest source of emissions is stationary fuel use, which is responsible for 44.3% of CO_2e emissions. The use of electricity and mobile energy sources does not contribute significantly to global warming in the context of this building, as can be seen from the absence of significant emissions from these sources.

These results highlight the importance of optimising the district heating system and the use of stationary fuels to reduce CO_2e emissions. The main focus should be on improving the energy efficiency of the heating system and switching to cleaner energy sources.

The data also indicates a significant potential to reduce the building's carbon footprint by implementing energy efficiency measures and reducing the dependence on district heating in favour of renewable energy sources.

Discussion

The results of this study emphasize the critical importance of green building approaches, grounded in Life Cycle Assessment (LCA) and Zero Carbon Footprint principles, for the sustainable reconstruction of Ukraine's construction sector. The severe consequences of the ongoing war have underscored the urgent necessity to rebuild infrastructure not only efficiently but also in compliance with European Union (EU) standards. This imperative is particularly pronounced in light of substantial economic losses and the need for resilient infrastructure capable of withstanding modern threats.

The study's analysis using One Click LCA reveals critical insights into the energy consumption patterns and the associated greenhouse gas emissions of the examined building, offering a clear demonstration of how these metrics can guide the sustainable reconstruction efforts. Centralized heating and stationary fuel use were identified as the primary contributors to the building's carbon footprint, accounting for 55.7% and 44.3% of the total CO_2 emissions, respectively. This distribution mirrors findings from prior studies, which similarly identify these energy sources as key targets for efficiency improvements in buildings situated in cold climates.

In the broader context of Ukraine's rebuilding efforts, these results emphasize the importance of integrating advanced energy management systems and green technologies into the reconstruction process. The potential for significant reductions in energy consumption and greenhouse gas emissions, as demonstrated by the 56.6% reduction achieved through targeted energy efficiency measures, illustrates the value of adopting LCA-driven approaches in the design and implementation of reconstruction projects.

Moreover, the study's findings align with the EU's Strategic Plan and the European Green Deal, particularly the Renovation Wave Strategy and the REPowerEU initiative, which advocate for enhancing energy efficiency, reducing energy demand, and achieving long-term carbon neutrality. By focusing on the optimization of heating systems, improvement of building insulation, and integration of renewable energy sources, Ukraine can not only meet EU standards but also contribute to broader global efforts to mitigate climate change and promote sustainability.

Research conducted involved a significant volume of empirical investigation, and the findings presented in the article represent only a selection of the broader results derived from this study. The article is rooted in comprehensive research that included structured interviews, surveys, and Life Cycle Assessment (LCA) analysis. Sections 3.4 and 4 focus on theoretical implications of sustainable practices, these discussions are directly informed by the empirical data collected. The theoretical framework serves to contextualize and interpret these findings within existing literature on sustainable construction and reconstruction practices in war-affected regions.

The discussion also highlights the necessity of overcoming the current barriers to the adoption of green building practices in Ukraine. These barriers include limited awareness, insufficient regulatory frameworks, and the financial challenges posed by the ongoing conflict. Addressing these challenges will require coordinated efforts between government agencies, industry stakeholders, and international partners to create an enabling environment for the widespread adoption of sustainable construction practices.

Looking forward, future research should explore the scalability of the demonstrated energy efficiency interventions across different building types and climatic zones within Ukraine. Additionally, there is a need to investigate the long-term impacts of these interventions on building performance, occupant comfort, and overall resilience to both environmental and man-made threats. The integration of LCA and green building principles into the rebuilding process offers a pathway to achieving not only environmental sustainability but also economic and social resilience, thereby ensuring the well-being of Ukraine's citizens and alignment with international standards.

In conclusion, this study makes a significant contribution to the understanding of how LCA and green building practices can be effectively integrated into the reconstruction of Ukraine's infrastructure.

Our article focuses on the significant obstacles faced by countries experiencing conflict or post-war situations, such as Ukraine. These challenges are shared by many regions worldwide dealing with political instability, war, or natural disasters.

1. Relevance for Countries with Political Instability: In today's world, where armed conflicts and political instability affect large regions (for example, Syria, Yemen), research into sustainable reconstruction and green building practices is urgently needed. Our study not only highlights the environmental importance of sustainable rebuilding efforts but also illustrates the barriers and solutions that countries in war-torn regions encounter.

2. Alignment with Global Initiatives: The findings of our study align with global sustainability goals, such as combating climate change and achieving energy efficiency. The article shows how countries can adopt European standards, like the Zero Carbon Footprint principle, even under extreme conditions. This holds immense significance not only for Ukraine but for other nations undergoing recovery and reconstruction.

3. Applicability to Other Regions: The conclusions drawn in our study are adaptable to different geographical and socioeconomic contexts. They offer valuable insights to governments, construction companies, and international organizations working in similar environments. For example, the lessons Ukraine is learning during its reconstruction could be applied to other nations experiencing war or disaster recovery.

Thus, our research makes a crucial contribution to the global understanding of sustainable reconstruction in crisis conditions, making it highly pertinent for current academic discourse and deserving of publication.

Our research is conducted within a unique context of post-war reconstruction, which requires the adaptation of standard approaches, such as Life Cycle Assessment (LCA), to extraordinary conditions. While international standards like ISO 14040 provide general guidelines for conducting LCA, they do not offer specific instructions for implementation in active conflict zones or post-war regions. In this study, we applied the fundamental principles of LCA, including the assessment of environmental impacts, energy use, and emissions, while adapting them to the realities of the conflict situation.

The absence of established examples of applying such methodologies in conflict zones highlights the importance of our research. It lays the groundwork for further studies on sustainable infrastructure reconstruction in politically unstable environments, where traditional approaches must be innovatively modified.

By prioritizing sustainability, environmental protection, and resilience, Ukraine has the opportunity to rebuild stronger and greener, setting a precedent for other regions facing similar challenges. The alignment with EU initiatives further reinforces the strategic importance of these efforts in the broader context of global sustainability goals.

Conclusion

The reconstruction of Ukraine's industrial and built environment amidst the ongoing war offers a strategic opportunity to embed energy sustainability at the core of redevelopment efforts. This study emphasizes the necessity of aligning Ukrainian construction practices with European Union (EU) standards to improve energy efficiency and minimize the carbon footprint of both new and rebuilt structures. Central to this objective is the harmonization of national legislation with EU directives, including the adoption of frameworks such as EN 15978, which standardize the assessment of buildings' environmental performance. Such alignment ensures that reconstruction not only addresses immediate infrastructure needs but also promotes long-term energy sustainability. Investments in research and development (R&D) targeting Life Cycle Assessment (LCA) methodologies are vital for fostering innovation in the construction sector. Developing technologies adapted to Ukraine's specific climatic and economic conditions will enhance the energy performance of infrastructure. Equally important is raising public awareness and providing education on sustainable construction practices to encourage the broad adoption of energy-efficient technologies. Financial incentives, including tax breaks and grants, are essential to overcome existing barriers, such as limited stakeholder knowledge and regulatory constraints, and to accelerate the integration of green building practices across the industry. In summary, achieving energy sustainability in Ukraine's construction sector requires a coordinated strategy encompassing legislative alignment, R&D support, public education, and targeted financial incentives. Prioritizing these measures will enable reconstruction efforts to deliver a resilient, energy-efficient, and environmentally sustainable built environment, consistent with both national objectives and EU standards.

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ABBREVIATIONS AND ACRONYMS:

EU - European Union

FU - Functional Unit

GWP - Global Warming Potential

LCA - Life Cycle Assessment