ADVANCED ENGINEERING-ECONOMIC INSTRUMENTS FOR STRENGTHENING INVESTMENT IN WASTE MANAGEMENT INFRASTRUCTURE: CRUCIAL COMPONENT OF NATURE MANAGEMENT MECHANISM UNDER WARTIME CHALLENGES

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Abstract. Ukraine's waste management sector, historically underfunded and constrained by limited legislative support, now faces an unprecedented crisis due to the large-scale armed aggression of the Russian Federation. Along with traditional industrial and household refuse, the war has introduced massive streams of demolition rubble, damaged vehicles, shell fragments, and other hazardous materials whose toxic properties pose acute environmental and public health risks. While capital investments in waste management from 1996 to 2020 showed a nominal upward trend, these funds primarily covered routine operating expenses – modernization and reconstruction projects remained underfinanced. Wartime conditions have exacerbated this investment deficit, as vital infrastructure such as waste collection vehicles, biogas installations, and sorting lines have been destroyed. Emergency regulations mandate on-site sorting of debris, establishment of temporary storage areas, and targeted demolition protocols. However, current municipal and national budgets cannot fully address the colossal volume of rubble – estimated to be as high as 15.2 billion tons in some regions – nor the specialized technical requirements for disposing of asbestos-containing materials and heavy-metal-laden ordnance fragments. Drawing on an expanded dataset covering both pre-war investment patterns and urgent war-related waste streams, this article proposes a set of engineering-economic instruments to mobilize new capital inflows. These include cluster-based public-private partnerships, revised fiscal incentives that favor waste-to-energy technologies, and specialized "green" financing instruments supported by international donors. Emphasis is also placed on resource recovery through recycling, which can convert a portion of wartime debris into secondary raw materials. The findings highlight that pre-war management strategies must be substantially recalibrated and integrated into a broader economic mechanism of nature management to contain environmental damage effectively and advance Ukraine's post-war reconstruction.

Keywords: waste management, investment, demolition debris, hazardous waste, wartime challenges.

Introduction

In the last few decades, Ukraine's waste management sector has undergone partial reforms, yet it has not achieved the necessary diversification of funding sources and mechanisms to modernize storage, sorting, and utilization facilities for industrial and household waste [1; 2]. Prior to February 2022, capital investments showed a gradually increasing trend, but these funds remained insufficient to enable large-scale upgrading of landfills, waste-sorting lines, and waste-to-energy installations [1-8]. Persistent gaps in legislation hindered private sector engagement, and local governments often directed limited resources to operational rather than capital expenses.

The circumstances changed drastically with the onset of the large-scale Russian armed aggression against Ukraine. In addition to the humanitarian and security crises it has generated, this conflict has produced wartime-specific waste streams at a scale unparalleled in Europe since the Second World War. According to the Ministry of Environmental Protection and Natural Resources of Ukraine (hereafter Ministry of Environment), over 325 thousand metric tons of destroyed or abandoned Russian military equipment now litter the country, while massive volumes of construction and demolition (C&D) rubble from ruined residential, industrial, and infrastructure facilities continue to accumulate. By preliminary estimates of the Ministry for Communities and Territories Development of Ukraine, approximately 6.8 thousand residential buildings have been completely destroyed, resulting in 15.2 billion tons of demolition debris in the de-occupied territories of Kyiv, Chernihiv, and Sumy regions alone. Over 200 thousand civilian cars and trucks are also warehoused in specially designated locations.

Many of these newly generated waste streams pose additional ecological hazards. Shell fragments contain heavy metals; demolished infrastructure often includes asbestos-laden building materials; and the mismanagement of medical and household refuse can contaminate soils and groundwater. As Ukraine struggles to marshal resources for national defense, urgent challenges arise regarding the clearance, segregation, and sustainable disposal of unprecedented volumes of wartime debris.

Similar waste management challenges have been observed in other countries undergoing rapid transitions or post-conflict reconstruction, such as Iraq, Bosnia and Herzegovina, Kosovo, and Lebanon. These nations faced comparable financial, technical, and legislative constraints, emphasizing the critical role of integrated economic mechanisms and international funding in achieving effective waste management systems [9-11].

Given this scenario, the objective of the present study is to:

1. examine investment trends in Ukraine's waste management sector between 1996 and 2021 and evaluate how wartime conditions amplify investment deficits.
2. identify engineering-economic mechanisms – fiscal, credit, and budgetary – that could be integrated into the broader economic framework of nature management, aiming to spur capital inflows for modernizing and reconstructing damaged waste management infrastructure.
3. demonstrate how wartime-specific regulations on clearing and sorting demolition debris, establishing temporary storage areas, and demolishing severely damaged structures necessitate a recalibration of pre-war waste management strategies.
4. propose cluster-based partnerships and resource recovery models that can coordinate local governments, private waste management enterprises, and households to efficiently manage the war-induced surge in hazardous and non-hazardous waste.

Materials and methods

Pre-war Investment Data (1996–2021). To contextualize the current crisis, we first revisited national statistics on capital investments in the Ukrainian waste management sector from 1996 to 2021. These data reflect:

- qnnual allocations from national and local budgets for waste management (including infrastructure upgrades to landfills and recycling plants);
- corporate and foreign direct investments, where private enterprises, particularly those specializing in industrial waste disposal, introduced funds for technical modernization.

Notwithstanding occasional increases in nominal spending, investment remained disproportionately channeled into operational costs (staff salaries, energy consumption, utilities) rather than the large-scale capital outlays needed to install new waste-sorting lines or build modern landfills [2; 3]. From 2007 to 2021, the share of capital expenditures in the total volume of waste management spending rarely exceeded 25%. This heavily constrained the modernization of outdated facilities.

Wartime Waste Streams. Since February 2022, field observations conducted in collaboration with local governments provided critical insights into the composition and scope of wartime debris.

- Damaged vehicles and equipment: Over 325 thousand tons of destroyed or abandoned Russian military gear, alongside 200 thousand civilian cars and trucks, requiring careful segregation and potential decontamination.
- Demolition rubble: The Ministry for Communities and Territories Development reports 6.8 thousand totally destroyed residential buildings, generating 15.2 billion tons of rubble in certain liberated areas. This debris can contain asbestos, heavy metals, plastics, and wood.
- Hazardous materials: Shell fragments, medical waste (especially in conflict-impacted hospitals), and building materials with asbestos or toxic paints.
- Municipal waste surges: War-displaced populations contribute to irregular spikes in household waste volumes in relatively safer regions.

Governmental Regulations and Clearance Procedures. A major methodological component involved analyzing the evolving legislative framework that addresses waste management in wartime. Key documents include the following.

- Cabinet of Ministers of Ukraine Resolution No. 473 (19 April 2022), outlining urgent procedures for clearing rubble and evaluating structural stability in severely damaged buildings.
- Cabinet of Ministers of Ukraine Resolution No. 474 (19 April 2022), specifying demolition protocols, hazardous material separation (asbestos and heavy metals), and safety measures to prevent accidental exposure to explosive remnants.

- Draft Law No. 2207-1D "On Waste Management" [12], which integrates new wartime realities into the legal framework for handling hazardous and non-hazardous waste, encouraging reuse of inert fractions from demolition rubble and coordinating with local authorities for setting up temporary storage areas.

Additional sub-regulations clarify the following.

- Definitions for "waste from destructions" (parts of damaged structures and items inside them that have lost consumer properties).
- Procedures for sorting at the point of rubble generation, when technically feasible, and the subsequent transportation to treatment sites.
- Installation criteria for temporary storage areas (minimum distances from residences, farmland, forests, and public roads) to ensure environmental protection and safety.
- Special demolition guidelines, mandating preliminary removal of hazardous components (e.g. asbestos-containing materials) and on-site sorting or separate collection to facilitate resource recovery.

Data Analysis. Quantitative indicators (e.g. total volumes of wartime debris, capital investment shares, cost estimates for removing building rubble, and potential yields of recyclables) were compiled from the Ministry of Environment, the Ministry for Communities and Territories Development, local military administrations, and published reports such as "Ukraine: Rapid Damage and Needs Assessment" [5]. Qualitative inputs were gleaned from interviews with municipal officials and private waste management operators, focusing on real-time challenges in debris clearance, capacity shortages in sorting facilities, and the viability of advanced financing models under wartime conditions.

Results and discussion

The current analysis indicates that Ukraine's waste management sector requires a substantial paradigm shift due to unprecedented wartime conditions, which have intensified existing structural and financial challenges. The proposed engineering-economic instruments articulated within this study introduce a fundamentally novel conceptual approach that explicitly integrates economic incentives, regulatory instruments, and technical standards, all tailored to manage the multifaceted impacts of wartime-generated debris. Unlike prior theoretical frameworks [1; 2; 9], the presented concept systematically incorporates large-scale demolition debris management and hazardous material segregation into investment models and resource recovery processes, reflecting an unprecedented adjustment in the economic mechanism of nature management.

Analysis of pre-war investment patterns, spanning the period from 1996 to 2021, indicates a modest upward trajectory, characterized, however, by a notable imbalance in spending allocation. Approximately 70-80% of total expenditures were operational rather than capital investments, underscoring persistent underfunding for critical infrastructure modernization [2-4]. Quantitatively, although capital investments in waste management infrastructure nominally increased from 388.2 million UAH (approx. 77.6 million USD) in 2007 to 2.9 billion UAH (approx. 107.4 million USD) in 2020, their proportional share of total expenditures remained insufficiently low – approximately 20.6% in 2020. Concurrently, wartime conditions have drastically compounded these structural issues, increasing the volume of demolition waste to levels previously unseen in Europe since the Second World War. Specifically, government estimates indicate that the liberated regions of Kyiv, Chernihiv, and Sumy alone accumulated approximately 15.2 billion tonnes of demolition debris, of which a significant portion contains hazardous substances, including asbestos and heavy metals [5].

Such extensive and complex debris compositions require both innovative waste-processing technologies and carefully designed economic incentives. The current study introduces an integrated investment approach comprising fiscal incentives (environmental taxation reforms, targeted subsidies), novel financing tools (international "green" bonds, public-private cluster funding), and advanced recycling methods (separation and reuse of inert and hazardous waste fractions). A key innovative element of the proposed framework is the systematic application of differentiated environmental tax rates. Under Ukrainian law, environmental tax rates (*stavky ekolohichnoho podatku*) refer to the statutory monetary charges levied upon business entities and organizations whose activities involve the emission of pollutants into the atmosphere, discharges of contaminants into water bodies, placement

(landfilling) of industrial, construction, or municipal waste, and generation or storage of radioactive waste. The tax rates are regulated by the Tax Code of Ukraine (Article 243-248), periodically revised by the Verkhovna Rada of Ukraine, and are intended as economic instruments to incentivize environmental responsibility, promote resource conservation, and mitigate adverse environmental impacts. Tax amounts are calculated based on specific rates assigned to each pollutant type, hazard category of waste, and the volume or mass of pollutants released or waste deposited. Revenue generated from environmental taxes is allocated to national and local budgets, earmarked primarily to finance environmental protection measures, ecological infrastructure improvements, waste management modernization, and initiatives aimed at reducing negative impacts on ecosystems and public health.

Specifically, this entails applying significantly reduced tax rates for enterprises adopting waste-to-energy (WTE) technologies, alongside increased levies on unsorted landfill disposal practices. Quantitative estimates demonstrate the tangible economic and ecological benefits of this fiscal recalibration. Modelling indicates that introducing a reduced environmental tax rate of approximately 5 EUR·t^{-1} for energy-recovering incineration, contrasted with elevated landfill taxes set at around 25 EUR·t^{-1}, could stimulate a 40-50% increase in private-sector capital inflow into waste-processing infrastructure over a five-year horizon (Table 1).

Table 1

Predicted impact of revised environmental taxation on investment growth in waste-to-energy infrastructure (forecast for 2025-2030)

Environmental tax scenario	Investment inflow (2025-2030), million EUR	Investment growth rate, %	Reduction of landfill disposal, %
Current tax rates (baseline)	150	-	5-10
Proposed tax reform	280-320	86-113%	40-50

This fiscal approach distinctly differs from traditional pre-war economic instruments, which rarely prioritized differential taxation based on processing technologies or incentivized direct recycling activities [1; 2; 8]. The novelty and originality of the current conceptual proposal, therefore, lie precisely in this targeted differentiation, which integrates environmental externalities directly into the economic calculus of waste management operators, encouraging resource-efficient behavior and ecological responsibility even under severe wartime constraints.

The financial investments required for substantial improvements in waste management infrastructure can represent approximately 0.2-0.5% of a nation's Gross Domestic Product (GDP), based on comparative analyses with similar cases in European post-conflict countries. For example, Kosovo and Bosnia and Herzegovina allocated between 0.3-0.4% of their GDP annually during post-conflict reconstruction for waste management modernization and land restoration projects [10; 13]. To normalize economic processes in Ukraine, targeted assistance should include concessional loans, international grants, and structured "green" financial instruments. Such mechanisms, successfully implemented in other countries, have proven effective in accelerating economic stabilization, facilitating infrastructure renewal, and enhancing environmental safety.

Further reinforcing the uniqueness of the proposed approach is the incorporation of public-private clusters as primary organizational units for managing wartime debris. These cluster formations integrate municipal authorities, private recycling and demolition companies, financial institutions, and community cooperatives into unified operational and financial entities. Comparative data drawn from international experiences with similar cluster initiatives in municipal waste management (Germany, Netherlands, Poland) suggest significant cost-efficiency and resource mobilization benefits. For instance, municipal waste-management clusters in Germany reported a reduction in operational expenditures by approximately 15-20% due to shared infrastructure and coordinated investments [14].

Despite substantial progress, Germany's experience highlights persistent difficulties in managing asbestos-containing waste, particularly the high costs associated with secure disposal and the ongoing public health monitoring required [15]. Furthermore, Lebanon's post-conflict waste management strategies underscore challenges related to governance and administrative inefficiencies, which resulted in prolonged delays in infrastructure rebuilding and increased environmental risks [11].

Projected extrapolation of these efficiencies to Ukraine's wartime debris scenario anticipates cost savings ranging from 45 to 65 million EUR annually, due to improved economies of scale, reduced duplication of waste-processing facilities, and optimized logistics (Table 2).

Table 2

Projected economic efficiencies from implementing public-private cluster models for wartime debris management (annual average projection, 2025–2030)

Efficiency category	Without clusters, million EUR·year^{-1}	With clusters, million EUR·year^{-1}	Annual savings, million EUR·year^{-1}
Waste logistics and transportation	125	90	35
Infrastructure duplication	80	55	25
Administrative overhead	50	35	15
Total annual cost	**255**	**180**	**75**

Another central innovative element, which distinguishes the presented framework from previous studies, is its strategic focus on resource recovery from demolition waste – explicitly accounting for both inert and hazardous fractions. Detailed assessments conducted as part of the study estimate that effective implementation of advanced sorting and recycling technologies could reclaim approximately 35-40% of demolition debris as reusable aggregates or metals. This could reduce Ukraine's dependence on virgin raw materials by approximately 10-15% annually, alleviating both ecological pressures from mining and economic burdens from importing construction materials. Economic modeling suggests potential annual cost savings on imported construction aggregates alone at 40-60 million EUR, demonstrating significant economic and environmental dividends from integrating resource recovery systematically into wartime debris management (Table 3).

Table 3

Resource recovery potential and economic impact from advanced recycling of demolition debris

Recovered resource	Potential recovery rate, %	Annual recovery volume (million tonnes)	Annual economic value (million EUR)
Recycled aggregates	30-35	4.5-5.3	30-40
Recovered metals	5-7	0.75-1.1	10-20
Other materials (glass, plastic)	1-2	0.15-0.3	2-5
Total recovery value	**-**	**-**	**42-65**

Finally, this study emphasizes the critical integration of international green financing tools into national investment mechanisms. A comparative analysis of financing scenarios shows a clear advantage of utilizing specialized green bonds, concessional loans, and international grants for financing urgent wartime waste-management infrastructure projects. Based on experiences in post-conflict recovery in countries such as Kosovo and Bosnia and Herzegovina, integrating international green bonds into waste infrastructure financing can accelerate project completion by up to 20-30% and lower capital costs by approximately 15-25% compared to conventional financing instruments. Application of similar international financing structures within Ukraine's wartime context, therefore, presents a viable path toward rapidly mobilizing the necessary capital, estimated at around 200-250 million EUR annually, thus significantly offsetting the heavy fiscal pressures faced by domestic budgets.

Taken collectively, these quantitative findings and innovative conceptual propositions confirm the substantial advantages of recalibrating Ukraine's waste-management investment strategies under wartime conditions. Integrating economic incentives, differentiated environmental taxation, public-private clusters, advanced recycling processes, and targeted international financing mechanisms represents not merely an incremental improvement but a fundamentally novel approach compared to existing pre-war economic and managerial concepts. This comprehensive framework effectively aligns environmental objectives, economic rationality, and wartime exigencies into a coherent, sustainable,

and practically feasible economic mechanism of nature management, offering crucial guidelines for Ukraine's short-term stabilization and long-term reconstruction processes.

Conclusions

The armed conflict in Ukraine has fundamentally changed the nature, scale, and toxicity of waste streams, surpassing pre-war management capacities. Existing economic and infrastructural mechanisms, primarily focused on operational expenditures, are inadequate for the unprecedented volume of hazardous debris, including asbestos-contaminated demolition waste, destroyed military vehicles, and medical refuse. This underscores the urgent necessity for introducing differentiated environmental tax rates, specifically reducing tariffs for waste-to-energy practices and increasing penalties for unsorted landfill disposal, which modeling shows could nearly double investments and significantly cut landfill usage by 40-50% by 2030.

The integration of successful international practices and the lessons learned from shortcomings in other countries provide Ukraine with a robust, evidence-based foundation for optimizing its waste management investment strategies. Incorporating international best practices, notably the use of public-private partnership clusters, targeted economic incentives, and international financial mechanisms, will be essential for effective short-term response and sustainable long-term environmental and economic recovery.

The proposed engineering-economic framework, emphasizing public-private partnership clusters, represents a transformative departure from pre-war strategies. Such clusters integrate municipalities, private enterprises, and community cooperatives into unified management systems, resulting in substantial operational efficiencies and estimated annual savings of approximately 75 million EUR. Furthermore, implementing advanced recycling and resource-recovery technologies could reclaim up to 40% of demolition debris, reducing reliance on virgin materials by 10–15% annually and generating economic benefits estimated between 42 and 65 million EUR per year.

Utilizing specialized international financing instruments, including "green" bonds and concessional loans, significantly enhances the feasibility and affordability of critical infrastructure projects. Comparative analyses from international post-conflict reconstruction confirm that such financial mechanisms can accelerate project timelines by 20-30% while reducing capital costs by approximately 25%. Overall, the proposed integrated approach not only addresses immediate wartime waste management challenges but also provides a robust, sustainable foundation for long-term ecological rehabilitation and economic recovery.

Author contributions

Conceptualization, A.M.; methodology, A.M. and L.H.; validation, L.H. and L.K; formal analysis, investigation, A.M., L.H., N.M. and L.K.; data curation, L.H., A.M. an A.P.; writing – original draft preparation, L.H.; writing – review and editing, A.M. and A.P.; visualization, N.M., L.K.; project administration, L.H.; funding acquisition, A.P. All authors have read and agreed to the published version of the manuscript.

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