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Circular economy strategies and environmental management in post-war recovery of Ukraine

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Abstract. The study analyzes the issue of rebuilding Ukrainian territories destroyed by military actions based on circular economy and environmental management. The analysis of pollution levels (Numbeo) in countries with military conflicts showed an average pollution level (62.1), which may influence the recovery process in Ukraine compared to countries with high pollution levels, such as Lebanon (89.4) and Syria (74.9). However, Ukraine has a low waste recycling rate (4.5%), which could complicate environmental recovery. The implementation of the circular economy in reconstructing Ukraine's infrastructure and the waste recycling process is suggested based on mobile laser sorting installations. The technology of mobile laser sorting installations allows efficient sorting of various materials, including metals, plastics, and construction debris, which can reduce recovery costs and optimize the use of available resources. To reduce environmental consequences and improve post-war recovery, it is suggested that pollution monitoring strategies be developed, investments in implementing the circular economy should be increased, and modern waste recycling technologies should be adopted. The analysis of the international experience in the recovery of affected regions highlights the importance of integrating environmental strategies into the recovery process, particularly by increasing the waste recycling rate and utilizing advanced technologies.

1. Introduction

The impact of military conflicts on the environmental component of settlements is becoming an increasingly pressing issue in today's unstable world. Military actions not only cause severe damage to the economy and social structure of countries, as can currently be observed in Ukraine, but also lead to significant environmental consequences that affect nature and human health for decades.

The destruction of ecosystems, pollution of air, water, and soil, and the loss of biodiversity are just a small part of the environmental damage that accompanies military conflicts.

This study examines the main environmental consequences of modern wars and their impact on the global resilience of ecosystems, while also suggesting ways to mitigate this damage in the context of international environmental protection efforts and the adoption of cutting-edge technologies from the perspective of circular economy principles.

Studying the impact of military conflicts on the environment is a challenging task to understand how the war affects both the natural world and humankind as a whole [1]. It is a subject of scientific research not only by scholars but also by social institutions and government representatives. Wars cause the destruction of ecosystems, alter the climatic conditions of affected regions, and create long-term environmental problems that can influence not only the conflict zones but also neighboring areas where indirect negative effects reduce the potential of both the territories and their inhabitants. The use of weapons of mass destruction, a prominent method of warfare in Ukraine, or the destruction of industrial and energy infrastructure often lead to air and water pollution, soil degradation, the death of local flora and fauna, the collapse of economic relations, psychological and emotional disorders in biological species, etc.

2. Literature review

Modern scientists are increasingly focusing on these issues, conducting research on the environmental consequences of military actions. Numerous research groups are studying the long-term effects of military conflicts using satellite monitoring, environmental assessments, and analyses of biological changes in conflict-affected regions. They document biodiversity losses, changes in soil composition, pollution of rivers and groundwater, as well as increased health risks for human beings. Besides, scientists are actively collaborating with policymakers, environmentalists, and international organizations at the international level to develop strategies aimed at minimizing environmental damage during armed conflicts and restoring destroyed ecosystems.

Gruia Bădescu notes that the reconstruction of cities after the war has now become a platform for international players who influence not only the course of military actions but also the recovery process [1].

Nour A. Munawar defines the political factor as the primary impact on post-war recovery and stresses the importance of establishing friendly relations with developed countries for rapid recovery [2].

Samir Makdisi and Raimundo Soto conclude that recovery policies should primarily focus on changes that improve the well-being of the population and the stabilization and restoration of existing systems [3].

A large number of scholars emphasize the need to focus efforts on ecosystem restoration after military conflicts, as there are already numerous suggestions on how to design sustainable, adaptive systems that can be applied to recover devastated territories [4].

Chinese scientists, who conducted diagnostics of key areas for ecosystem restoration based on the multi-scale spatial morphology of surface-line-point, offer targeted strategies for territorial restoration at the surface-line-point level, namely at the macro, meso, and micro levels, taking into account the specific features of each object and regional development [5].

The heterogeneity of landscapes and infrastructure facilities requires a more thorough analysis and the involvement of local communities during the recovery period. However, as scientists point out in their research, the foundation should be eco-friendly construction and state-of-the-art technologies [6].

Since the territory of Ukraine is also a rich resource land that has biodiversity and creates potential for the development of tourism, a major loss from military operations is the destruction of biosystems. The importance of the post-war period for incorporating biodiversity priorities into reconstruction and recovery efforts is also paramount, the scientists note. Considering this, the circular economy will help restore natural potential faster [7].

The question of the resource crisis after hostilities is widely analyzed even now, as the number of conflicts is increasing. However, reconstruction is a complex systemic process that requires a lot of time, technology and resources. Linnér, Björn-Ola reminds us that global problems are not yet solved, and engineering solutions must be used with innovation in mind, otherwise resources will be used irrationally, while statistics emphasize the aggravation of global problems [8].

Also, scientists note that military intervention primarily affects the infrastructure of settlements, as the destruction of health care infrastructure is observed during wars, which can lead to the weakening of the Prevention Program or cause the emergence of new strains of infectious diseases. In turn, the population weakened by stress is fragile and needs international assistance and the creation of new recovery systems [9].

Urban systems are dynamic in nature, and the ecology of settlements is technological. Now the ecology of cities is open and depends also on government, politics and community. It seeks to avoid disinterestedness, unlimited irrationality, and single sets of values. When smart technologies are accessible to different groups in society, they can improve the functionality of urban systems and their subsystems, such as "green" urban biological ecosystems. The Blue Belt has become a widespread model for many cities as a way to provide a variety of ecosystem services, including stormwater management, water quality improvement, wildlife habitat, environmental education, and property value enhancement, so it should be used in Ukraine as well. Traditionally, cities create value by serving as economic centers, bringing together diverse people, so their regeneration requires strict planning and consideration of a large number of loads, which is not possible without circular principles of economic management [10].

At the same time, in small settlements, it is necessary to involve the latest technologies in the creation of a useful product of manual labor, which is possible with the involvement of secondary raw materials. Such work will help highlight global issues and give a second life to resources and generate additional income for residents [11].

Ukrainian scientists note that it is important to use an integrated project approach when restoring the territories of Ukraine. At the same time, it is noted that very often road maps are not implemented, and the implementation of programs is delayed, so the authors emphasize that with the help of mathematical models and algorithms it becomes possible to control infrastructure parameters project products within the program, taking into account factors such as costs, duration and interests of interesting pages, and complex and uncertain infrastructure projects require an integrated approach to program relationship management and change forecasting [12].

Since there are a large number of approaches to the recovery of Ukraine, the article used analytical research methods and questionnaire method to adapt existing approaches, use foreign experience, and create recommendations for rapid ecological and economic recovery [12].

3. Results

Studies also highlight the need for international regulation of military technologies and strategies to prevent catastrophic environmental consequences. The major military conflicts of the past decades are shown in Table 1.

Table 1. The world's major military conflicts over the past decades and macroeconomic indicators of the affected countries [13].

Country	Year	Estimated cost of restoration (billion USD)	GDP per capita (USD, 2023)	Donor countries	Waste recycling rate (%)	Pollution rate (Numbeo)	Human Development Index (HDI)
Iraq	2003	55	5,800 USD	USA, UK, Japan, EU	15.4	72.5	0.686
Syria	2011-2020	250	1,200 USD	EU, USA, Saudi Arabia, UAE	2	74.9	0.575
Bosnia and Herzegovina	1992-1995	37	7,200 USD	EU, USA, Japan	23.8	59.8	0.78
Ukraine (assessment)	2022	411	4,000 USD	EU, USA, Canada, Japan	4.5	62.1	0.773
Lebanon	2006	7	3,400 USD	Saudi Arabia, Kuwait, Qatar	9	89.4	0.706

When considering the estimated cost of territorial recovery, attention should be given to the following indicators: the highest recovery costs have been assessed for Ukraine (411 billion USD) and Syria (250 billion USD), reflecting the extensive destruction caused by prolonged and intense conflicts in these countries. The recovery costs for Iraq following the 2003 conflict amounted to 55 billion USD, which is also significant but considerably lower than the estimates for Ukraine and Syria. Meanwhile, the cost of recovery for Lebanon (7 billion USD) and Bosnia and Herzegovina (37 billion USD) is relatively lower, likely due to the smaller scale of conflicts in these regions.

Analyzing ecosystem losses, the highest level of pollution is observed in Lebanon (89.4) and Syria (74.9), indicating serious environmental issues. In contrast, Bosnia and Herzegovina and Ukraine exhibit moderate pollution levels (59.8 and 62.1).

Analyzing the development of countries, Bosnia and Herzegovina has the highest Human Development Index (HDI) of 0.78 followed closely by Ukraine with the HDI of 0.773, indicating relatively better living conditions. In contrast, Syria has the lowest HDI of 0.575, likely the result of prolonged conflict and infrastructure destruction. When examining the waste recycling rate as an indicator of development and the introduction of advanced technologies, Bosnia and Herzegovina and Iraq exhibit the highest recycling levels, reflecting well-established waste management systems even after conflicts. Meanwhile, Ukraine still prioritizes waste disposal through landfilling, which negatively affects the quality of life in the studied territories.

According to Table 1, it is essential to thoroughly investigate the recovery of such countries as Ukraine and Syria, as these states face the highest estimated recovery costs. They require significant international investments and long-term support programs to rebuild their infrastructure and economies. Special attention should be paid to waste recycling as an alternative way for territorial recovery, particularly since the recycling rates are critically low in these areas. Investing in the appropriate infrastructure and training can significantly reduce the environmental burden. Implementing environmental programs in Lebanon and Syria to lower pollution levels will enhance living conditions and public health while creating favorable conditions for rapid territorial recovery. Additionally, social and economic development programs should focus on improving the quality of life in Syria and Iraq, particularly by enhancing access to education, healthcare, and social services.

Ukraine has faced significant destruction due to military actions with the estimated recovery cost of 411 billion USD. This includes the restoration of infrastructure, housing, economic activity, as well as social and economic development. Key challenges include the damaged infrastructure, population displacement, economic decline, environmental consequences, and the need for international support.

Fig. 1 illustrates the main recovery strategies for the territories of Ukraine, taking into account positive experience of recovery from other countries that have experienced military conflicts in areas where citizens reside.

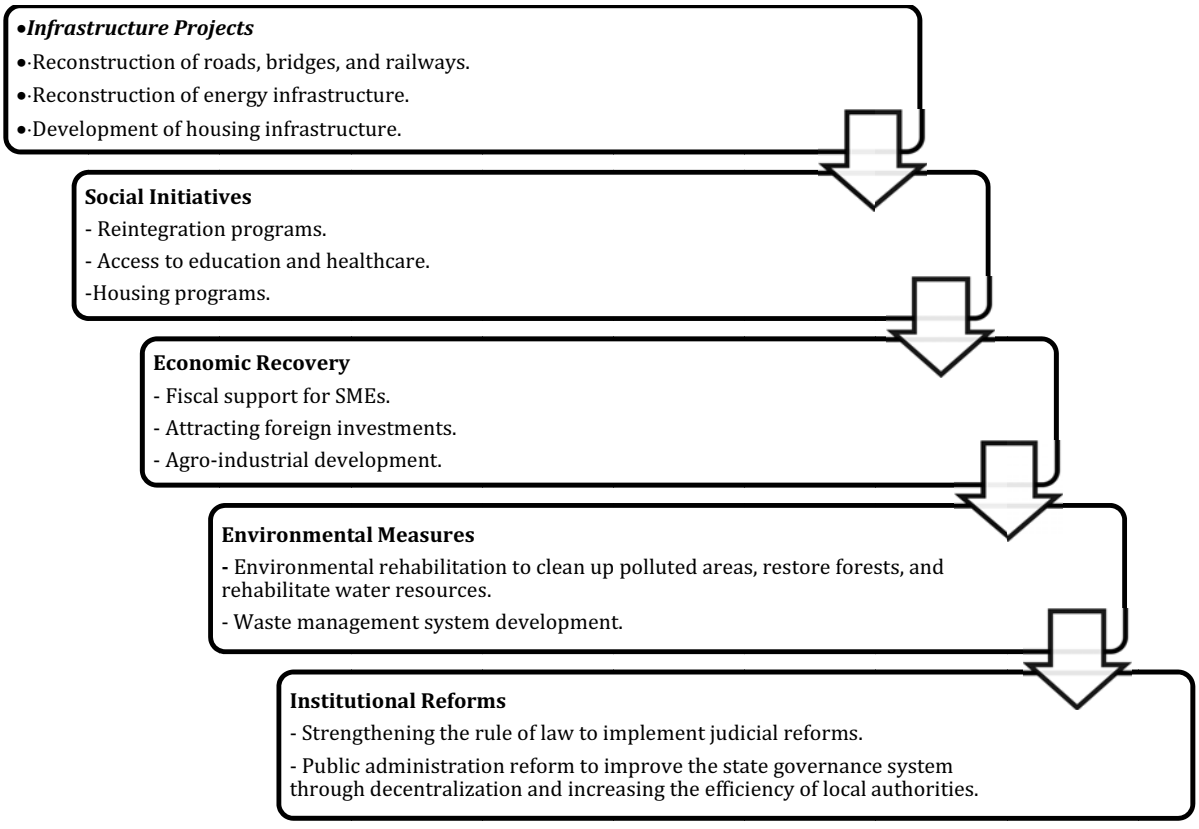

Figure 1. Key strategies and areas for Ukraine's post-war recovery.

Fig. 1 shows that achieving the goal of reconstructing Ukraine to improve living standards of the population requires systemic changes and the introduction of innovative solutions.

The environmental component is the foundation for the successful functioning of other systems and a reserve for increasing the country's economic level.

The introduction of the circular economy in settlements during reconstruction is a necessary step to ensure sustainable development in the face of growing environmental and economic challenges. The traditional linear economy based on the extract-produce-use-dispose model leads to significant resource losses, the generation of large amounts of waste, and the deterioration of environmental conditions.

On the other hand, the circular economy focuses on keeping resources in circulation for as long as possible through reuse, recovery, and recycling, which reduces the environmental impact.

The scientific rationale for the need to implement the circular economy in cities is based on several key factors: reducing resource dependency, decreasing waste volumes, minimizing the environmental footprint, achieving economic benefits, and addressing social aspects.

Implementing the circular economy in cities requires systemic changes in resource management, the creation of effective infrastructure for recycling and reusing materials, and active citizen participation in changing consumption patterns.

The foundation for implementing the circular economy is waste sorting, which is a key element of the environmental policy in developed countries aimed at the rational use of resources, reducing waste, and minimizing negative environmental impacts. This practical measure supports the concept of sustainable development and the circular economy. The reasons why developed countries actively implement waste sorting systems can be explained from both scientific and economic perspectives:

- Reducing the volume of waste in landfills allows separating valuable materials for recycling, thereby decreasing the amount of waste that goes to landfills. This helps extend the lifespan of existing landfills and reduces the need to create new ones, which is crucial for the preservation of natural areas.

- Resource and energy savings by recycling secondary materials such as glass, plastic, metal, and paper, which requires significantly less energy than producing these materials from primary resources.

- Reduction of greenhouse gas emissions, which is achievable by decreasing the amount of organic waste decomposing in landfills, thus reducing methane emissions, one of the most potent greenhouse gases. Separate collection of organic waste for composting or biogas production helps cut methane emissions. Besides, recycling materials requires less energy than producing from primary sources, thereby reducing CO2 emissions into the atmosphere.

- Stimulation of the circular economy, as waste sorting serves as the foundation for implementing circular economic models and facilitates the return of resources to the production cycle, minimizing the consumption of new materials and creating a favorable economic climate for international development.

- Social responsibility and environmental consciousness reflected in the recognition of the importance of environmental protection and individual contributions to the sustainable future. Environmental education and promotion at the state level encourage citizen participation in waste sorting.

- Legislative requirements enforced by strict environmental laws and regulations that oblige citizens and companies to sort waste.

Violations of these requirements can result in fines and other penalties. The government policy stimulates waste sorting by setting recycling and disposal goals, as well as creating the necessary infrastructure for these processes.

Given the above mentioned, it can be concluded that waste sorting in developed countries is a strategic approach to waste management aimed at minimizing environmental damage, conserving resources, and building a more sustainable economy.

Taking into account this, a table has been created listing modern sorting facilities that could be installed in Ukraine to restore territories in case of restructuring existing waste management systems.

Table 2. Cost and characteristics of mobile laser sorting installations.

Brand	Model	Price (USD)	Capacity (tons per hour)	Description
REDWAVE	REDWAVE XRF Mobile	1,000.000 – 1,500.000	50 - 150	Mobile installation with XRF and laser sensors for sorting various materials, including metals and construction debris.
TOMRA	COMBISENSE Mobile	800,000 – 1,200.000	30 - 100	Comprehensive mobile installation with multi-sensor technology, including laser sorting.
Binder+Co	MINEX Mobile	700,000 – 1,100.000	20 - 80	Mobile installation for sorting mineral materials and construction debris using laser and optical sensors.
Terex Finlay	FINLAY 883+ Mobile	600,000 – 900,000	40 - 120	Mobile sorting complex with the capability to integrate laser systems for sorting construction debris and ore.
Sesotec	VARISORT Mobile	750,000 – 1,250.000	25 - 90	Mobile installation with laser sorting and optical sensors for recycling plastics and metals.

Table 2 allows concluding that financial donors for the implementation of environmental projects in Ukraine makes it possible to maximize the utilization of waste generated as a result of military actions. This will allow for the rational use of available resources and reduce the costs of rebuilding Ukrainian settlements. European companies, such as the Holcim French company, that use secondary raw materials for construction have positive experience in creating resource-efficient settlements [14-16].

When shifting to the circular economy, there is a concern that jobs in traditional professions will decrease. However, the Circular Jobs Initiative by Circle Economy, in collaboration with the International Labour Organization and the World Bank, focuses on leveraging the circular economy to create stable, inclusive jobs. It emphasizes that additional education and innovative qualifications will lead to the emergence of new jobs and funding opportunities. Partnerships with policymakers, enterprises, and communities will facilitate systemic changes and ensure that the shift to the circular economy benefits both the environment and workers [17-19].

To implement a circular economy in city construction, a comprehensive mathematical model can be used that will take into account various factors related to the design, construction, operation and disposal of construction projects. The formula can be based on an assessment of the efficiency of resource use, waste minimization and reuse of materials. An example of a mathematical formula for assessing a circular economy in construction may look in formula 1.

$$E_c = \frac{\sum_{i=1}^{n}(M_{reuse,i} - M_{recycle,i}) - V_{total}}{R_{total}} \quad (1)$$

Ec — circular economy efficiency index,

Mreuse, i — mass of materials reused for i i-th object,

Mrecycle, i — mass of recycled materials for i-th object,

Wtotal — total volume of waste from all construction objects,

Rtotal — total volume of resources used for construction.

This formula allows us to assess the degree of circularity of the economy in construction by comparing the amount of reused and recycled materials with the total amount of resources and waste. A high Ec indicates a more sustainable and efficient construction model that is in line with the principles of a circular economy.

For example the result Ec in Kyiv =0.12 means that the circular economy index for this city is 0.12 or 12%. This means that 12% of the materials in the city's construction are either reused or recycled, which demonstrates a certain level of sustainability, but there is still room for improvement.

Energy-saving measures such as the use of renewable energy sources and energy-efficient buildings can reduce energy consumption in cities by 20–40%. The use of circular principles in construction and operation allows saving up to 30% of the total energy consumption in cities. In circular cities, it is possible to reduce the consumption of primary resources (e.g. water, minerals, building materials) by 20–50%. This is especially relevant in construction – through the secondary use of materials and their recycling, it is possible to reduce raw material costs by 30%.

According to an anonymous survey in Ukraine, out of 300 respondents, the population widely supports the introduction of a circular economy. Only 8% of respondents are not familiar with this concept, and 17% of respondents are ready to actively help with the introduction of a circular economy in the restoration of Ukraine. 94% of the surveyed activists are the population under 30 years old, which shows the interest of young people in changes and stabilization of the situation in the country. Officials of municipal infrastructure facilities turned out to be passive in decisions, so we can call this segment of the population dangerous for innovative restoration and an uninitiated part of the population. This indicates the need to update the management apparatus and effectively involve young people in the restoration. To improve the results, we propose using the positive experience of countries and conducting ongoing explanatory work and training for the population and managers, conducting trainings and involving foreign delegates and companies in the restoration.

International initiatives supporting the circular economy include such well-known organizations as Circle Economy, the Ellen MacArthur Foundation, Closed Loop Partners, Intesa Sanpaolo, EIT Climate-KIC, Plug and Play Tech Center, Circular Economy Accelerator, ING Bank, etc. This highlights the availability of support for environmental projects and the potential to seek funding for implementing the circular economy in Ukraine due to international donors.

One of the best examples of implementing the circular economy is the Netherlands that has set ambitious goals to achieve the 100% circular economy by 2050. The Netherlands actively

develops waste recycling, resource reuse, stimulates circular business models and technologies, implements environmental education, and employs strategies to promote sustainable behavior among citizens. It has launched extensive programs to support startups and companies operating in this field and created strong legislation for shifting to closed resource cycles, which can serve as an excellent model for other countries. The country has primarily added provisions to its legislation that encourage research and the implementation of circular business models through tax breaks and subsidies, which has significantly boosted changes among business representatives [20-21].

For Ukraine, it would be a priority to increase investment and combat the shadow economy. Scientists write that it is necessary to constantly monitor the results of foreign companies' activities in Ukraine and provide an opportunity to implement domestic projects, as well as strive for openness of data and reports [22].

4. Discussion

The implementation of the circular economy in Ukraine, as in other countries, is accompanied by a number of controversial issues and challenges. At present, Ukraine lacks a clear and comprehensive legal framework for the implementation of the circular economy. Legislation requires updating to support recycling, reuse of materials and waste management. Issues related to tax incentives for enterprises that use secondary resources remain relevant. Stricter liability for waste management is also needed, which requires coordination between ministries and local authorities. Ukraine has an insufficiently developed waste recycling infrastructure. It is estimated that less than 10% of municipal solid waste is recycled, the rest goes to landfills. To transition to a circular economy, significant investments are needed in upgrading infrastructure, creating recycling plants and optimizing waste collection. One of the most discussed issues is the lack of economic incentives for businesses.

The implementation of circular models requires significant investments, but many companies face a lack of financing, especially small and medium-sized businesses. Tax incentives, subsidies and support for green investments are being discussed to accelerate this process. The circular economy requires high awareness among the population and businesses. At the moment, the level of environmental awareness in Ukraine remains low, and many consumers do not understand the importance of recycling and reusing resources. This leads to discussions about the need for large-scale educational and information campaigns to raise awareness of the circular economy and its benefits. The transition to a circular economy can affect the labor market. On the one hand, the creation of jobs in the field of recycling and repair of materials can be a plus. On the other hand, the transition can cause problems for traditional sectors of the economy, especially if appropriate retraining of workers is not ensured. As Ukraine moves towards European integration, an important debatable issue is the harmonization of Ukrainian legislation with European standards in the field of ecology and waste management. The European Green Deal provides strict requirements for reducing emissions and recycling resources, and Ukraine needs to decide how to adapt its systems to these standards and eradicate corruption. Thus, the implementation of a circular economy in Ukraine requires the resolution of many controversial issues at the level of politics, finance and infrastructure, which requires a comprehensive approach and the active participation of the state, business and society.

5. Conclusions

The military conflict in Ukraine has a significant and long-lasting impact on the environment of the entire country and surrounding territories. As a result of hostilities, natural ecosystems are being destroyed, soils, water bodies, and the atmosphere are being polluted with toxic substances, large-scale fires are occurring, while infrastructure, biocenosis, and economic systems are being damaged. Major environmental threats include emissions of heavy metals, toxic chemicals, oil, and other pollutants resulting from explosions and the destruction of industrial and infrastructure facilities, as well as disruptions in waste management and energy systems. In addition to the direct impact on the environment, the conflict exacerbates climate issues, which may have long-term consequences for human health and the biosphere as a whole. To minimize environmental consequences, urgent measures are needed for environmental restoration, pollution monitoring, and the development of strategies for rehabilitating affected ecosystems based on the principles of the circular environmental system as an alternative to traditional market economies.

The analysis of the experience of post-war recovery in various countries shows that successful post-conflict rehabilitation requires a comprehensive approach, including social, economic, environmental, and political reforms. Restoring ecology, infrastructure, resource management, supporting affected populations, and reintegrating socially vulnerable groups are key factors in the stabilization process, and Ukraine has significant potential for success in these areas. Particular attention should be given to restoring the ecological and economic situation, attracting investments, and establishing resilient institutions to support long-term stability. The experience of different countries shows that international assistance plays an important role; however, the main driver of successful recovery remains national efforts and efficient resource management. It is advisable for donor countries providing financial and material innovative resources to be developed nations with experience in post-war recovery of other countries. These could include the EU countries, the USA, the UK, Japan, and developed friendly countries in the Middle East.

To enhance the effectiveness of post-war reconstruction of settlements, it is suggested to use mobile laser sorting installations for recycling construction materials, marking a significant step forward in sustainable construction and waste management.

These technologies enable efficient separation of construction waste into components for further secondary use, reducing the amount of waste sent to landfills and decreasing the need for extracting primary materials. Mobile installations offer several advantages, including flexibility in application at various construction sites, increased speed and accuracy of sorting, and reduced waste transportation costs. Their use contributes to lowering the carbon footprint of the construction industry, supports the principles of the circular economy, and promotes the creation of more sustainable cities.

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