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Estimating the Carbon Footprint of Post-War Reconstruction: Toward a "Greener" Recovery of Ukraine

Toru Kobayakawa[*]

Abstract

Along with the significant investment required for Ukraine's post-war reconstruction, the rebuilding process will likely result in substantial carbon dioxide (CO2) emissions. This study estimated the CO2 footprint of Ukraine's reconstruction using an environmentally extended multi-region input-output (MRIO) analysis. The results revealed that the carbon footprint during a ten-year reconstruction phase is expected to be 4.3 times Ukraine's annual territorial CO2 emissions before the war. More than half of these emissions are estimated to be generated by Ukraine's construction industry, indicating an urgent need to reduce emissions through industry modernization and efficiency improvements. Additionally, approximately 13% of the indirect CO2 emissions are anticipated to come from the production of building materials such as concrete and steel. Therefore, effective efforts must be made to curb these emissions by maximizing the recycling of materials from debris. Such measures are expected not only to significantly reduce CO2 emissions during Ukraine's restoration and reconstruction phase but also to lead to the creation of new industries and prepare the country for potential future EU membership.

Keywords: Ukraine reconstruction, carbon footprint, infrastructure development, scrap recycling

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1. Introduction

Following the Russian invasion of Ukraine that began in February 2022, a significant amount of infrastructure has been destroyed. Rebuilding this Ukrainian infrastructure is necessary for restoration and reconstruction once landmines and debris have been removed. The World Bank, the Government of Ukraine, the European Union, and the United Nations have jointly conducted a rapid needs assessment (RDNA). According to the third assessment (RDNA3), published in February 2024, the cost of direct damage amounts to \$152 billion, with an estimated \$486 billion required for restoration and reconstruction. The reconstruction aims to build better infrastructure than before the invasion, under the concept of "Build Back Better," which focuses on creating more modern and environmentally friendly systems that will be key to future EU membership (World Bank 2022).

Regarding the impact of Russia's invasion of Ukraine on climate change, some publications have estimated the increased greenhouse gas (GHG) emissions due to the war (Chepeliev et al. 2023; Bun et al. 2024) and discussed how to achieve energy systems and societies with reduced GHG emissions after restoration and reconstruction (Kuzemko et al. 2022; Keim and Sydorovych 2024). However, there is limited research on the carbon dioxide (CO_2) emissions associated with infrastructure reconstruction (de Klerk et al. 2023). Generally, infrastructure construction demands substantial energy for the operation of construction machinery and requires construction materials like concrete and steel, which emit large amounts of CO_2 during production. In reconstructing Ukraine's infrastructure, it is crucial to adopt technologies that emit less CO_2 during the operational phase (flow). It is also vital to minimize CO_2 emissions during the construction phase (stock).

This study aims to estimate the carbon (CO_2) footprint associated with the reconstruction of Ukraine using an environmentally extended multi-region input-output (MRIO) analysis. Further, it proposes feasible measures to reduce the carbon footprint of the reconstruction process. Although there are various standards regarding how carbon footprint (CF) should be calculated, this study employs the definition of CF suggested by Wiedmann and Minx (2008), which considers CO_2 emissions only,[1] without including other GHGs. The rest of the paper is organized as follows: Section 2 introduces the data and methods employed. Section 3 presents the results of the analyses. Section 4 discusses the results and the limitations, and Section 5 summarizes the findings and discusses areas for future research.

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[1] Emissions of CO_2 include all fossil CO_2 sources, such as fossil fuel combustion, non-metallic mineral processes (e.g., cement production), metal (ferrous and non-ferrous) production processes, urea production, agricultural liming and solvent use. Sources and sinks from land use, land-use change, and forestry (LULUCF) are excluded.

2. Data and Methods

2.1 Multi-Regional Input-Output Analysis

In this study, the carbon footprint is calculated by using Input-Output (I-O) analysis, which is a well-known tool for exploring the entire supply chain and the associated ("embodied") emissions from each upstream stage of the supply chain of a commodity (Wiedmann 2009). Using the basic Leontief model, the I-O framework can be written as:

$$x = Ax + y \tag{1}$$

$$x = (I - A)^{-1} y = Ly \tag{2}$$

where x is the total output of one economy, Ax is intermediate consumption, y is final consumption, I is the identity matrix, and L is known as the Leontief inverse matrix, which captures both direct and indirect economic inputs to satisfy one unit of final demand in monetary value (Leontief 1936). The I-O model can be scaled up to include several regions, which gives the MRIO models. With the environmental intensity vector e representing the CO_2 emissions per unit of industry output, the vector of carbon footprint (CF) for each sector can be formulated as:

$$CF = \hat{e}x = \hat{e}Ly = \hat{e}L(y_{pc} + y_{gc} + y_{gfcf} + y_{ci} + y_{ex}) \tag{3}$$

where the final consumption (y) is the summation of household consumption (y_{pc}), government consumption (y_{gc}), gross fixed capital formation (y_{gfcf}), change in inventory (y_{ci}), and exports to the other regions (y_{ex}). The environmental intensity vector (e) is diagonalized. Thus, the carbon footprint resulting from GFCF (CF_{gfcf}) can be extracted from the above equation:

$$CF_{gfcf} = \hat{e}Ly_{gfcf} \tag{4}$$

Several MRIO models provide necessary data for computation, namely the I-O production coefficient matrix (A), the CO_2 emission intensity (e), and the disaggregated final demand of GFCF (y_{gfcf}). In this study, Eora26 is employed as it is one of a few MRIO models that covers Ukraine.

2.2 Data

This study's primary data source is the Eora26 database[2], a set of global MRIO tables that cover 189 specific countries with 26-sector classification per country and include a continuous time series from 1990 onwards (Lenzen et al. 2012; 2013). The advantage of using the Eora26 database is that harmonization procedures are applied to ensure international comparability throughout the data collection effort, ensuring data quality and minimizing the risk of measurement errors. Due

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[2] https://new.worldmrio.com/eora26/

to data availability, the Eora26 table for 2016 is used in this study.

Regarding the disaggregated final demand of GFCF (y_{gfcf}) to be substituted into equation (4), the costs required for reconstruction estimated in RDNA3 (over the ten years from 2024 to 2033) are used. RDNA3 estimates costs for each major sector's necessary infrastructure, materials, and activities (Figure 1). The estimated costs in RDNA3 are reclassified into the sectors in Eora26 through the following two steps:

(i) According to the cost breakdowns indicated in RDNA3, the activities and investments can be roughly categorized into (a) infrastructure construction for respective major sectors, (b) vehicle procurement, (c) equipment procurement, (d) business activities, and (e) public administration. Preparatory works for infrastructure construction, such as surveys, fall under (d). Government programs such as institutional strengthening activities fall under (e).

(ii) Given the definitions of the Eora26 sectors indicated in Table 1 (Piñero et al. 2018; United Nations 2002), the conversion of the costs in RDNA3 into the Eora26 sectors is performed according to the concordance matrix shown in Table 2. It is to be noted that category (a) accompanies investments in various sectors of Eora26 as it involves not only construction works but also inputs such as construction materials, machinery, equipment, and business activities, including designing works. The cost proportions of each item used in this study are based on various publicly available data for the different types of infrastructure (Goldwyn et al. 2020; JICA 1996; Liu, Lu, and Al-Hussein 2014; Pauschert 2009; Gulczyński and Przybyła 2010; Rafiq et al. 2021). It is also assumed that the costs indicated as "Recovery and Reconstruction Needs" in the RDNA3 are estimated based on basic prices. However, considering that the details of the costing measures are known and that the costs of individual infrastructure should vary depending on different conditions and types of technologies, these breakdowns are merely rough estimations based on certain assumptions. The one-to-one conversion is possible for categories (b)-(e) since the Eora26 database has the corresponding sector.

Since the Eora26 table of 2016 is used, the final demand of GFCF is adjusted by using the consumer price index.

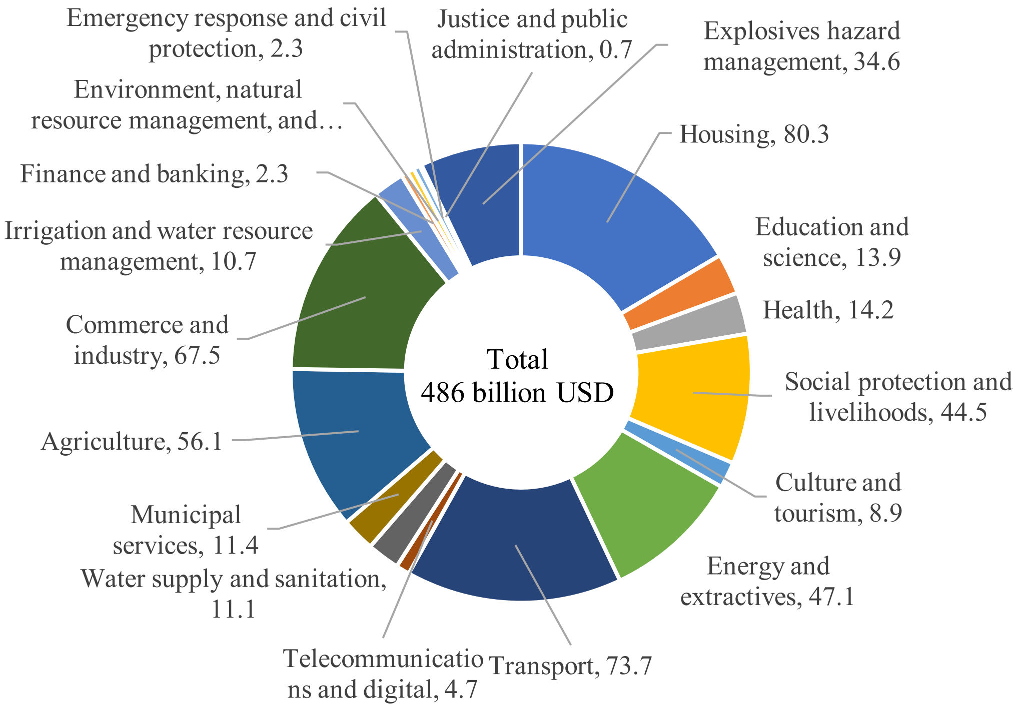

Figure 1: Total reconstruction needs estimated in RDNA3 (bil. USD)

Source: World Bank 2022

Table 1: Definitions of the relevant Eora sectors

Eora sector	Definition
Petroleum, chemical and non-metallic mineral products	Manufacture of coke, refined petroleum products, and nuclear fuel; chemicals and chemical products; rubber and plastics products; other non-metallic mineral products.
Metal products	Manufacture of basic metals; fabricated metal products (excluding machinery and equipment).
Electrical and machinery	Manufacture of machinery and equipment; electrical machinery and apparatus; radio, television, and communication equipment.
Transport equipment	Manufacture of motor vehicles, trailers, and semi-trailers; other transport equipment.
Construction	Site preparation; building of complete constructions or parts thereof; civil engineering (excluding manufacture of building materials; installing industrial equipment, etc.).
Financial and business activities	Financial intermediation; real estate activities; research and development; other business activities.
Public administration	Administration of the State and the economic and social policy of the community.

Source: Piñero et al. 2018, and United Nations 2002

Table 2: Cost proportions of the RDNA3 items in terms of the Eora26 sectors

Eora sectors / RDNA3 items	Petroleum, chemical and non-metallic mineral products	Metal products	Electrical and machinery	Transport equipment	Construction	Financial and business activities	Public admin
(a) Infrastructure							
Housing & building	20%	15%	10%		50%	5%	
Energy generation	5%	5%	75%		10%	5%	
Energy transmission	5%	35%	15%		40%	5%	
Roads	65%				30%	5%	
Bridges	30%	25%			40%	5%	
Railways	20%	10%	15%	10%	40%	5%	
Water & irrigation	30%	25%	20%		20%	5%	
(b) Vehicle				100%			
(c) Equipment			100%				
(d) Business activities						100%	
(e) Public admin							100%

Note: This table is used for converting the costs of the RDNA items into the costs in terms of the Eora26 sectors. For example, the costs of "energy generation" items categorized under RDAN3 are allocated in terms of the Eora26 sectors as follows: 5% for "Petroleum, chemical and non-metallic mineral products," 5% for "Metal products," 75% for "Electrical and machinery," 10% for "Construction," and 5% for "Financial and business activities."

Source: Author's calculation and Goldwyn et al. 2020, JICA 1996, Liu, Lu and Al-Hussein 2014, Pauschert 2009, Gulczyński and Przybyła 2010, and Rafiq et al. 2021

3. Results

Suppose the necessary reconstruction investment of 486 billion USD is carried out over ten years. In that case, 781 million tons (Mt) of CO_2 will be emitted, of which 87% will be incurred domestically, with the remainder occurring outside of Ukraine. Figure 2 shows the cost breakdown according to the Eora26 sectors, while Figure 3 shows the corresponding carbon footprints. The carbon footprint from the construction industry has the highest share at 57%, followed by business activities (14%), electrical and machinery (11%), non-metal products (7%), metal products (6%), government activities (4%), and transport equipment (1%).

For a better understanding, the total emissions of 781 Mt can be expressed as either of the following examples (EDGAR 2023):

- 4.3 years' worth of Ukraine's pre-war annual territorial CO_2 emissions (181 Mt in 2021);
- 28% of annual territorial CO_2 emissions of the EU27 (2,805 Mt in 2022);
- Annual territorial CO_2 emissions of Germany (634 Mt) and the Netherlands (135 Mt) combined in 2022.

Even assuming that the reconstruction will take ten years, the impact on climate change is not negligible.

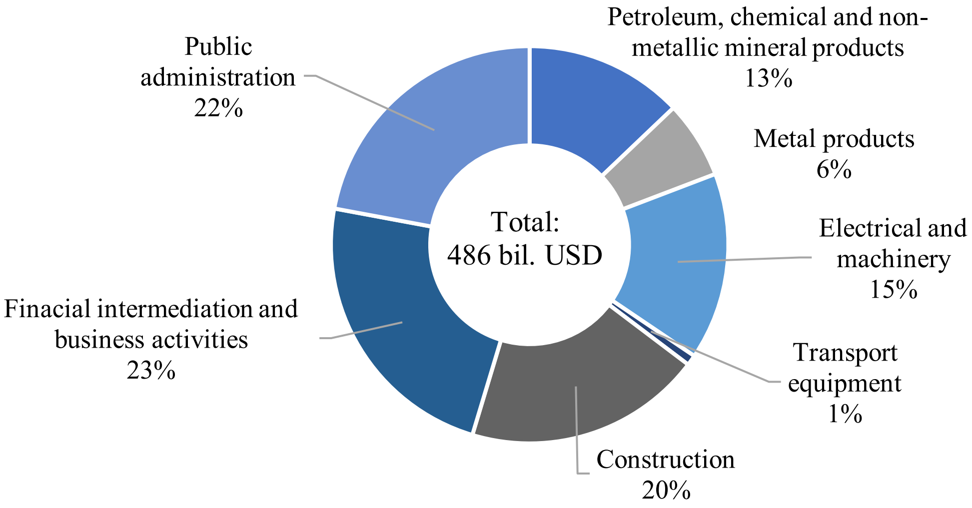

Figure 2: Investments by sector

Source: Author's calculation and World Bank 2022

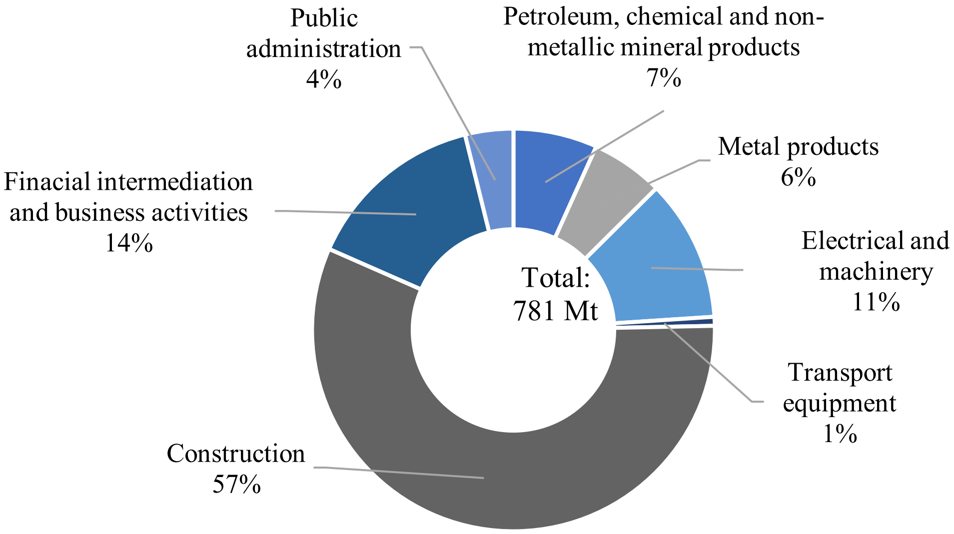

Figure 3: Carbon footprints by sector

Source: Author's calculation

4. Discussion

A crucial indicator for Ukraine's so-called Green Recovery will be how the country can establish its social and economic system with reduced GHG emissions levels after restoration and reconstruction. However, as mentioned above, the carbon footprints during the infrastructure rebuilding process are significant, and thus, all efforts should be made to minimize them. For this purpose, two different approaches are discussed in the following sections.

4.1 Modernization of the Ukrainian Construction Industry

Considering that more than half of the carbon footprint comes from the construction sector, it is essential to modernize and enhance the industry's efficiency, thereby reducing its emission factor. In fact, the emission factor of the Ukrainian construction industry is notably higher than the world average, largely attributable to inefficiencies in business and engineering practices. Key issues previously identified in the Ukrainian construction industry include high levels of opacity, inefficient use of resources and process management, and ineffective design and construction management, which lead to reduced labor productivity and frequent rework (Markina et al. 2019; Trach et al. 2021). The Ukrainian construction industry needs to undertake significant modernization of design and process management, possibly through collaborations with foreign partners. International financial institutions (IFIs) can also enhance their engagement with the industry by increasing the number of internationally funded projects and enforcing guidelines to ensure transparency and fairness during the implementation process.

Table 3 shows the simulation results of the carbon footprint reduction with a lower emission factor for the construction sector in Ukraine. As the sector's share of the carbon footprint is sizable at 57%, applying the emission factor of the German construction sector, which is approximately ten times lower according to the Eora26 database, would significantly reduce the total carbon footprint of reconstruction.

Table 3: Effects of lower emission factors for the domestic construction industry

Scenario	Effects of CF reduction
● Improving the emission factor of the construction sector to the level of Germany	Reduction of 309.1 Mt, equivalent to Poland's annual territorial CO_2 emissions (322.0 Mt in 2022)

Source: Author's calculation and EDGAR 2023

4.2 Facilitation of material recycling for reconstruction

More concrete methods include using recycled materials for construction—e.g., concrete and steel—that emit considerable amounts of CO_2 during manufacturing. In the case of steel, production from scrap using electric arc furnaces emits only 10–25% of the CO_2 compared to conventional blast furnaces (Sahoo et al. 2019; Fan and Friedmann 2021). Another analysis shows that construction and demolition waste recycling could be an effective mitigation option to reduce energy consumption and offset greenhouse gas emissions, where about 39% is attributed to the construction industry; recover added-value materials, create jobs, and protect the earth's natural resources (Alsheyab 2022). In Ukraine, because of the large amounts of debris already generated and the future overwhelming scale of reconstruction needs, recycling construction materials would not only help reduce GHG emissions but also offer various additional benefits, including the creation of new industries and employment.

Table 4 shows the simulation results of the carbon footprint reduction with two scenarios of lower emission factors for material (metal and non-metal) production in Ukraine. Since the carbon footprint resulting from the material inputs is significant—with a collective share of 13%—reducing emission factors by promoting waste recycling could generate prominent positive effects in reducing the total carbon footprint of reconstruction. More accurate simulations will be required in future studies, taking into consideration factors such as the foreseeable amounts of debris, collection and recycling rates, improvements in emission factors, etc.

Table 4: Effects of lower emission factors for domestic material production

Scenario	Effects of CF reduction
● Improving the emission factor of non-metal/metal product sectors by 10%	Reduction of 7.2 Mt, equivalent to the annual CO_2 emission of a 1100MW coal-fired power plant.
● Improving the emission factor of non-metal/metal product sectors by 50%	Reduction of 36.1 Mt, equivalent to Sweden's annual territorial CO_2 emission (37.9 Mt in 2022).

Source: Author's calculation, IEA 2020, and EDGAR 2023

4.3 Limitations

We have made several assumptions in converting RDNA3's cost breakdown into the Eora26 sectors (Table 2). The estimated carbon footprint could vary depending on these hypotheses. If available, more detailed information about the projects listed by RDNA3 would help to enhance the accuracy of the results.

Moreover, the global trade structure might have changed following the Russian invasion in February 2022 and subsequent economic sanctions, potentially leading to changes in MRIO (Almazán-Gómez et al. 2024; Haddad et al. 2023; Hrynevych, Blanco Canto, and Jiménez García. 2023). Potential structural changes have not been considered in this study since the Eora26 table for 2016 was used. For more accurate predictions, it will be necessary to wait for the latest MRIO to be compiled.

5. Conclusion

The carbon footprint resulting from Ukraine's expected restoration and reconstruction is estimated at 781 Mt. Enhancing the efficiency of Ukraine's construction industry is crucial in the reconstruction process. The modernization of the construction industry should be pursued not only from an engineering aspect but also from an institutional aspect, supported by instructions and guidance from the government and financing institutions.

It has also been found that increasing the recycling rates of construction materials such as steel and concrete would significantly reduce CO_2 emissions. Ukraine’s steel industry primarily uses blast furnaces, and introducing electric arc furnaces for recycling will require new investments but contribute to industrial revitalization. Furthermore, advancing rubble recycling is expected to create new jobs. New technologies for green steel and low-carbon concrete production are being developed. Besides recycling, actively introducing such technologies is expected to strengthen the industrial competitiveness of post-war Ukraine in view of the reconstruction process and the EU’s forthcoming introduction of the Carbon Border Adjustment Mechanism (CBAM).

This study focused on the reconstruction of Ukraine’s infrastructure, which has suffered significant damage during the war. However, infrastructure construction and renewal are also carried out daily in countries other than Ukraine, and the CO_2 emissions associated with such activities cannot be ignored (Kobayakawa 2022). Considering the increasing threat posed by climate change, it has become critical to assess measures to estimate and reduce CO_2 emissions at the design stage of infrastructure construction. The overall impact of CO_2 emissions resulting from the reconstruction of any particular infrastructure needs to be assessed during both the construction stage and the operation stage. Further studies will be valuable in determining what infrastructure construction is desirable to mitigate climate change effectively.

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Abstract (in Japanese)

要　約

2022年2月に始まったロシアの侵略によって、ウクライナでは電力や運輸に関連する多くのインフラストラクチャーが破壊された。復旧・復興のためには、地雷の除去やがれきの処分に続いて、これらのインフラの再建が必要となる。世銀、国連、EU、ウクライナ政府は共同でRapid Needs Assessment（RDNA）を3度にわたって実施した。2024年2月に発表されたRDNA3によると、直接的な被害額は1,520億ドル、復旧・復興に必要となる費用は4,860億ドルと試算されている。再建に際しては、将来的なEU加盟も見据えつつ、侵略の前よりもより良いインフラを建設すること（Build Back Better）を目指し、より近代的で環境負荷の低いものとなることを志向している。

ロシアのウクライナ侵略が気候変動に与える影響に関しては、戦争によって増加した温室効果ガス（GHG）排出量を推計した文献、戦争によって復旧・復興後にいかにGHG排出量を抑制したエネルギーシステムや社会を実現できるかを論じた文献などが発表されているが、インフラ再建に伴って排出される二酸化炭素（CO_2）についての研究は少ない。一般にインフラ建設では、建機等の稼働に多くのエネルギーが必要であることに加え、コンクリートや鉄鋼などの製造過程で大量のCO_2を排出する建設資材を投入することが求められる。ウクライナのインフラ再建に当たっては、供用段階で排出するCO_2（フロー）が少ない技術を導入していくことが重要であるが、これとあわせて建設段階で排出するCO_2（ストック）についても可能な限り抑制していく必要がある。

本研究では、産業連関表を用いたライフサイクル評価によって、ウクライナの再建に伴って排出されるCO_2量（「カーボン・フットプリント」という）を試算した。この結果、復興時のインフラ建設等には戦争開始前のウクライナの4.3年分のCO_2排出量を伴うことが明らかになった。排出量の半分以上がウクライナの建設業界から排出されることから、当該業界の近代化と効率化が急務である。また、コンクリートや鉄鋼といった建設資材の製造に伴う排出量が約13%を占めることから、がれき等からの資材のリサイクルを進めることが、復興時のカーボン・フットプリントを抑制する上で効果的と考えられる。

キーワード： ウクライナ復興、カーボン・フットプリント、インフラ開発、廃棄物の再利用