https://doi.org/10.33271/nvngu/2025-6/246

S. V. Ilchenko,
orcid.org/0000-0002-8052-8678

State Organization "Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine", Kyiv, Ukraine
* Corresponding author e-mail: ilchenko.svit@gmail.com

INDICATIVE MODEL OF THE ECO-ADAPTIVE MODERNIZATION OF UKRAINE'S TRANSPORT AND LOGISTIC NETWORK

Purpose. To develop a scientifically grounded indicative model for the eco-adaptive modernization of Ukraine's transport and logistic network, and to assess the degree of its environmental adaptation to the imperatives of sustainable development, taking into account the spatial-structural transformation of the network and the contemporary ecological challenges.

Methodology. This study employs an indicative approach to assessing the environmental adaptation of Ukraine's Transport & Logistic network (TLN), grounded in the construction of a multi-indicator model. The model incorporates a set of indicators: CO_2 emissions in the transport sector, the degree of electrification of transport fleets, the development of multimodal freight operations, the energy efficiency of transport infrastructure, and the volume of external environmental costs. Based on normalized values, a regional Environmental Adaptation Index (EAI) was constructed, alongside an integrated "green" corridor rating (ECOLOGIS) for Ukraine's logistics corridors. The methodology also encompasses spatial analysis, regional clustering according to adaptation levels, and evaluation of structural shifts in modal logistics induced by wartime disruptions.

Findings. A regional assessment of the environmental adaptation of Ukraine's transport and logistic network was conducted, enabling the classification of regions into high, medium, and low levels of adaptation to the challenges of sustainable development. The analysis revealed that the greatest ecological potential is concentrated within logistics corridors dominated by electrified and multimodal transport flows. Significant spatial disparities were identified in the ecological-structural profiles of regions, thereby delineating strategic priorities for further infrastructure modernization.

Originality. The scientific novelty lies in the development of an indicative model for the ecological-adaptive modernization of Ukraine's TLN, including the Environmental Adaptation Index and the ECOLOGIS assessment system for spatial diagnostics and prioritization of sustainable post-war infrastructure development.

Practical value. This study provides an applied analytical framework for evaluating the environmental adaptation of Ukraine's Transport & Logistics network in response to the demands of sustainable development and the intensifying ecological pressure of wartime. The proposed instruments enable the justification of infrastructure modernization priorities, enhance the effectiveness of spatial planning, and support informed decision-making on the environmental upgrading of transport systems at both national and regional governance levels.

Keywords: *transport & logistic network, environmental adaptation, sustainable development, spatial-structural transformation*

Introduction. The transport and logistic system (TLS) constitute a critical pillar of the spatial and economic organization of the national economy, shaping mobility dynamics, resource interconnectivity, and the resilience of production-consumption linkages. Not only is its functional evolution increasingly driven by techno-economic imperatives, but also by the demands of socio-ecological transformation. Amid escalating climate risks, ongoing energy transitions, and mounting geopolitical tension, the need to reconceptualize logistics development models through the lens of environmental efficiency, adaptive capacity, and spatial equilibrium becomes particularly salient. The structural complexity of transport logistics – and its interlinkages with energy systems, industrial production, export chains, and urban agglomerations – generates both positive multiplier effects and mounting pressure on the environment.

Despite some progress in infrastructure modernization prior to the full-scale war, Ukraine's TLS remained energy-intensive, predominantly unimodal, and insufficiently aligned with environmental priorities. The dominance of road transport (over 55 % of freight turnover) [1], underutilization of railways, inland waterways (IWW), and multimodal (MM) hubs were accompanied by high CO_2 emissions (reaching up to 38 million tonnes per year), critical depreciation of the vehicle fleet [1], and a lack of institutional capacity to implement a coherent green transport policy. Spatial freight flows were primarily concentrated along the north-south axis and the central-western corridor, while the eastern regions remained only partially integrated into balanced logistics networks. The full-scale invasion of 2022 triggered a profound disruption of logistics routes, widespread destruction of transport infrastructure, overloading of road transport, a deepening of regional imbalances, and escalating socio-environmental costs. As a result of modal imbalance, loss of ports and logistics hubs, and intensified environmental stress, the challenge of adapting logistics networks to a radically altered landscape has acquired critical urgency.

At the same time, the ecological adaptation of the TLS understood as the capacity of infrastructure, modal configurations, and governance mechanisms to align with the principles of sustainable development – remains largely absent from bot@h academic discourse and applied policy analysis. The lack of an integrated approach to assessing ecological adaptation, particularly one that incorporates spatial characteristics and sustainability indicators, significantly hampers the formulation of coherent and effective transport policy. This underscores the imperative to develop an indicative model capable of providing a comprehensive assessment of the ecological adaptation status of Ukraine's TLS. Such a model must account for regional disparities, shifts in modal structure, levels of institutional readiness, energy intensity, and the scale of environmental challenges, which have been exacerbated by the ongoing war. The proposed model is intended to serve as a foundation for spatial diagnostics, strategic planning, and the environmentally oriented modernization of logistics infrastructure during the post-war recovery phase.

Literature review. The development of TLS in the context of current imperatives – climate neutrality, energy transition, and infrastructure resilience – necessitates reliance on consolidated international standards and strategic frameworks. These instruments establish the conceptual, regulatory, and methodological foundations for the ecological modernization of the transport sector, defining pathways for its alignment with sustainable development objectives. Of particular significance are policy documents issued under the auspices of the United Nations. Within the framework of the newly proposed Methodology for Enhancing Climate Ambition and Advancing Transport Policy [2], a structured model for integrating TLS into national climate plans (NDCs) is introduced, while the Paris Climate Agreement [3] identifies the transport sector as a priority target for decarbonization. These overarching frameworks are further reinforced by an interagency UN report [4], which embeds transport withing the broader climate and socio-economic agenda of global sustainable development.

From the standpoint of economic efficiency and institutional capacity for modernization, notable approaches have been developed within the frameworks of the United Nations and the World Bank. In particular, key documents [5, 6] offer conceptual foundations for environmentally sustainable transport, methods for the indicative assessment of externalities, and strategies for the integration of ecological considerations into national transport policies. These foundations have been further elaborated by the International Transport Forum (ITF), whose report [7] emphasizes the systemic vulnerability of transport infrastructure to climate, energy, and geopolitical risks. Within the European Union, the most advanced regulatory architecture supporting the green transformation of transport infrastructure has been established. Central to this framework are the provisions of the European Green Deal [8] and the Sustainable and Smart Mobility Strategy [9], both of which aim to achieve climate neutrality in the transport sector by 2050. Key priorities include the electrification of vehicle fleets, the expansion of multimodal transport systems, the modal shift of freight to environmentally preferable modes (rail. Inland, waterways), and the enhanced use of digital tools for monitoring and optimizing logistics operations.

A comprehensive toolkit for planning and assessing the environmental performance of transport infrastructure has been proposed in a number of international documents, notably in report [10]. These emphasise the integration of climate resilience criteria into infrastructure investment processes, the development of vulnerability indicators, and the formulation of logistics models adapted to global environmental change.

A distinct dimension is represented by regulatory documents focused on the sustainable development of freight transport and multimodal logistics solutions. These include: [11], which is aimed at establishing resilient supply chains while accounting for external environmental effects; [12], an intergovernmental agreement on the development of environmentally-oriented dry ports as key nodes of transnational logistics; [13], which presents an ecosystem-based approach to the development of liner transport infrastructure, incorporating considerations of biodiversity, habitat fragmentation, and landscape integration; [14], an analytical overview offering a taxonomy of emerging mobility forms along with a framework of indicators for assessing their environmental performance, efficiency, and safety.

A dedicated set of environmental regulatory instruments for TLN is consolidated within the EU's legislative framework, which combines binding regulations and strategic directives aimed at decarbonization, energy efficiency, and digitalization of the sector. Among the key legal acts are: Regulation (EU) 2019/631, setting CO_2 emission targets for passenger cars; Regulation (EU) 2019/1242, concerning heavy-duty vehicles; Directive 2014/94/EU on the promotion of clean and energy-efficient vehicles in public procurement; Directive 2014/94/EU on road user charges for heavy goods vehicles; Directive 2012/27/EU on energy efficiency; Regulation (EU) 2020/852 on the taxonomy for sustainable investments; and Regulation (EU) 2021/1153 establishing the Connecting Europe Facility (CEF) as a key funding mechanism for sustainable transport infrastructure. Substantively, these legal acts focus on improving resource efficiency in transport, incentivizing the shift towards low-carbon technologies, expanding electric vehicle charging networks, supporting multimodality and inland waterways, and institutionalizing indicator-based environmental impact monitoring.

Thus, the international regulatory framework for transport greening provides a coherent set of reference points for the development of national strategies for adaptive modernization of TLN, ensuring the integration of environmental, infrastructural, and spatial priorities of sustainable development.

Over the past decade, there has been a growing scholarly interest in the greening of TLS, driven by both global climate imperatives and the need to adapt infrastructure to the principles of sustainable development. Studies [15, 16] substantiate the necessity of developing sustainable and "smart" logistics hubs as key components of Ukraine's transport system integration with the EU, and propose methodologies for assessing the environmental performance of railway stations. Authors [17, 18] highlight the importance of integrating sustainable KPIs into sectoral governance mechanisms and the need to adapt the strategies of transport enterprises to wartime conditions. In works [19, 20], emphasis is placed on the synergy between green and digital transformations during post-war recovery, with a focus on prioritizing railway transport. Meanwhile, article [21] argues for the formation of a new transport education paradigm to ensure the human capital base for implementing ecological transformation in the sector. Taken together, these studies reflect a multidimensional approach to greening TLS, encompassing infrastructure, governance, digitalization, and education, and provide a methodological foundation for developing a model of sustainable modernization of Ukraine's TLN.

Unsolved aspects of the problem. Despite the existence of numerous studies on the sustainable development of transport logistics, several critical dimensions remain insufficiently addressed. Foremost among these is the absence of comprehensive indicative models that incorporate spatial and structural differentiation, thereby enabling a meaningful assessment of the ecological adaptation of TLN to the Sustainable Development Goals (SDG). The consequences of structural shifts triggered by the war – particularly the increased burden on road transport and the disruption of multimodal infrastructure – remain inadequately explored. Moreover, there is a notable lack of tools for clustering regions based on their level of ecological adaptation, as well as an absence of integrated indicators to evaluate the sustainability of logistics corridors. In addition, environmental priorities remain poorly embedded within transport police, significantly constraining the implementation of adaptive strategies aligned with sustainable development.

The purpose of the article is to develop a scientifically grounded indicative model for the ecological and adaptive modernization of Ukraine's TLB and to assess their level of ecological adaptation to the requirements of sustainable development, taking into account spatial-structural transformations and the escalating environmental challenges intensified by the war.

Methods. In the post-war period, the ecological transformation of Ukraine's TLN must be grounded both in a strategic vision of long-term priorities and in a scientifically substantiated system of quantitative assessment. Such a system serves as a pivotal instrument for implementing the SDG, ensuring compliance with European regulatory standards, and enhancing the effectiveness of policymaking. The methodological foundation of this system is based on an interdisciplinary approach that integrates the principles of sustainable development, transport logistics, ecological economics, and spatial planning. The synergy of these conceptual frameworks ensures both the quantitative measurability of indicators and their political and economic relevance.

Given the specificities of the wartime and post-war context, the Ukrainian model of indicative assessment provides for the adaptation of international experience to conditions marked by infrastructure degradation, reconfiguration of logistical flows, and recovery needs. The proposed system constructed on a spatial-cluster principle, enabling its application at the national and regional levels, as well as within individual transport-logistics hubs and corridors. It established a comprehensive toolkit for strategic planning, evaluation of sustainable development programmes, investment prioritisation, and mobilization of international financing. To ensure clarity of interpretation within the model, distinct temporal horizons are defined: short-term (up to 1 year) for operational response, medium-term (1 to 3 years), and long-term (over 3 years). The structure of the indicative system compares five functional blocks: CO_2 emissions level, share of electrified transport, degree of multimodality, energy efficiency of transport infrastructure, and volume of external environmental costs. Each block is assigned indicative target values (benchmarks) aligned with EU regulatory requirements – Regulations (EU) 2019/631, 2019/1242, and 2023/1805 – as well as with strategic initiatives such as European Green Deal, the Fit for 55 Package, and the Sustainable and Smart Mobility Strategy. To reinforce the theoretical and methodological basis for assessing the ecological adaptation of TLNs, the development of the modal incorporates international practices in green logistics indicator systems [22, 23]. Specifically, approaches adapted from source [24, 25] have been applied, taking into account the impacts of war, structural degradation of transport infrastructure, and shifts in modal composition. This methodological integration enhances the validity of the selected indicators and ensures alignment with the targets of the European Green Deal and the criteria set by international financial institutions.

The hierarchical logic of assessment comprises three analytical tiers: national (compliance with Ukraine's international obligations), regional (diagnostics of territorial disparities and ecological risks), and cluster level (evaluation of sustainability within localised logistics systems). Each indicator block is directly aligned with existing European financing instruments – such as the Connecting Europe Facility (CEF), LIFE Programme, and the Innovation Fund – which significantly enhances their managerial relevance and practical applicability in the context of sustainable logistics transformation. The Integrated Environmental Adaptation Index (IAEI) is calculated as the arithmetic mean of the normalised values of the respective indicator, thereby providing a robust quantitative measure of the ecological maturity of a given TLS

$$IEA_i = \frac{1}{n}\sum_{k=1}^{n} x_{normik},$$

where IEA_i denotes the integrated environmental adaptation for region i; x_{normik} represents the normalised value of indicator k in region i; n is the total number of indicators (in this case, $n = 5$).

Normalisation is conducted using the min-max procedure. For positive indicators (i.e., those for which higher values indicate better performance), the formula is as follows

$$x_{normki} = \frac{x_{ik} - x_k^{\min}}{x_k^{\max} - x_k^{\min}},$$

where x_{ik} is the actual (initial) value of the k^{th} indicator for region i; $x_k^{\min}$ and $x_k^{\max}$ are the minimum and maximum values of the k^{th} indicator across all regions under analysis, respectively.

For negative indicators (i.e., those where lower values signify better environmental performance), inverse normalization is applied using the formula

$$x_{normik} = \frac{x_k^{\max} - x_{ik}}{x_k^{\max} - x_k^{\min}}.$$

A distinctive feature of the proposed methodology lies in the application of expert adjustments to reflect structural, spatial, and institutional specificities that are not captured by conventional statistics. These may include the particularities of a region's transport profile, asymmetries in logistical flows, or the presence of strategic adaptation programmes. As such, the proposed system constitutes a hybrid evaluative model, integrating quantitative objectivity with quantitative flexibility. It provides a robust foundation for evidence-based governance of the ecological modernisation of Ukraine's transport sector.

Within the scope of this research, the term "*ecological modernisation*" is conceptualised as a systemic process of structural transformation in TLN, aimed as reducing environmental impact through the deployment of advanced technologies, innovative management practices, and spatial reconfiguration. "*Adaptation*" is defined as the capacity of logistics systems to respond to external challenges (notably war-related risks and climate change) by adjusting their parameters towards sustainability. The notion of "*ecological efficiency*" is employed to describe the ration of achieved environmental outcomes (e.g. emission reductions, decline in external costs) to resources expended. "*Green investment*" refers to capital allocations aimed at enhancing the resilience and environmental performance of transport infrastructure, in alignment with EU criteria (EU Taxonomy, Green Deal, Fit for 55).

Results. The Russian armed aggression against Ukraine has profoundly reshaped the spatial, functional, and institutional configuration of the country's TLN [26]. It has led to the disruption of the traditional freight corridor, the disintegration of the eastern logistics core, and a reorientation of the national logistics paradigm – from a "door-export" model to a "defence-humanitarian" one in the early months of the war, and subsequently towards an adaptation-driven export model.

One of the most significant consequences has been the loss or blocked of key infrastructure nodes – including the seaports along the Black Sea and the Sea of Azov, railway connections with the industrial clusters of Donetsk region, as well as the critical degradation of logistics in frontline areas. According to estimates by the World Bank and the Government of Ukraine, direct losses to logistics infrastructure in 2022–2023 exceeded USD 9 billion, excluding indirect losses arising from supply chain disruption, congestion of alternative routes, and the degradation of logistics services.

In response of these challenges, Ukraine underwent an accelerated reallocation of logistical flows (Table 1).

1. Reorientation toward the Western vector – through logistics corridors to Poland, Slovakia, Hungary, and Romania.

2. Activation of railway infrastructure in western regions: the Lviv, Zakarpattia, Volyn, and Rivne oblasts experienced a sharp increase in logistical loads, including agro-exports (grain, oil, feed), defence-related imports, humanitarian aid, and construction materials. For instance, freight volumes surged through the Yahodyn-Dorohusk rail crossing, while terminal facilities in Kovel, Chop, and Uzhhorod underwent modernisation.

3. Growing importance of domestic multimodal solutions, particularly in the segment of short logistics chains. Following the disruption of traditional trunk routes and the blockade of seaports, a new infrastructure emerged consisting of warehouses, sorting hubs, and transshipment platforms near railway stations, road hubs, and border checkpoints. These developments enabled the organization of both first-mile (from producer to hub) and last-mile (from hub to consumer of border) logistics under resource-constrained conditions.

Table 1

Spatial reorientation of logistics, 2022–2024

Direction/Aspects	Before the war	After the invasion	Implementation example
East → West	Export of metals, ore, coal via Mariupol, Berdiansk, Mykolaiv	New routes via Uzhhorod, Chop, Yahodyn, Mostyska; western boarded crossings	Kryvyi Rih → Uzhhorod with reloading to EU gauge
South → Danube region	Agro-export via ports of Odesa, Pivdennyi, Mykolaiv	Growing role of Reni and Izmail ports; private terminals under construction; up to 30 % of grain via theDanube	From Kirovohrad region → Izmail → barge shipment on the Danube
South/Central → Northern corridor	Supplies via seaports and southern hubs	Imports of critical goods via Kyiv-Zhytomyr-Lutsk; crossings at polish and Slovak boarders	Import of construction materials via western corridors (Kyiv – Zhytomyr – Lutsk)
Activation of Western rail infrastructure		Increasing freight volumes, modernization of crossings (Yahodyn, Chop), terminal construction	Agro-export via Yahodyn-Kovel, Chop station modernization
Formation of a multimodal cluster of the Danube		Development of Reni, and Izmail ports, barge transshipment, grain elevators, investments	Over 10 mln tons of cargo through Izmail port in 2023, new elevators and terminals
Reactivation of border road crossing		Increased load on EU border checkpoints, introduction of electronic queue, capacity expansion	Congestion at Shehyni-Medyka crossing, launch of e-queue system, logistics platform at Porubne
Reorientation of routes to central regions		Shift of logistics chains to central oblasts: warehouses, terminals, transshipment	New routed through Koziatyn, Khmilnyk, Zhmerynka; relief of Kyiv logistic hub
Localization of logistics centres near safe clusters		Creation of temporary hubs and warehouses in safer regions	Industrial warehouse in Khmelnytskyi, logistics nodes in Kamianets-Podilskyi

Such solutions have become a critical element of flexible logistics under wartime volatility and laid the groundwork for deeper modal integration, especially between road and rail transport.

4. Adaptive repurposing of logistics operators, including the integration of cargo transportation with distribution logistics functions, and the partial revival of freight routes via the Danube River.

Particular attention should be given to the formation of a new multimodal Danube logistics cluster (comprising the ports of Reni, Izmail, and Kilia), which under wartime conditions emerged as a critical alternative route for the export of agricultural products, oil, and metal goods. The region has witnessed the development of new terminals, grain elevators, and barge transshipment facilities, constructed with the involvement of private investors and international donors.

Prior to 2022, Ukraine's domestic freight structure maintained a relatively stable modal balance: road transport accounted for approximately 55 % of total freight turnover, rail transport for 42 %, and inland waterways for no more than 3 % [1]. However, during 2022–2023, according to the World Bank estimates, this structure underwent radical transformation. As access to maritime ports was lost, parts of the railway network in the east were destroyed, and logistics were reoriented toward the western corridor, the share of road transport surged to over 70 %, while road transport fell to 25–27 %.

This modal shift significantly increased the energy intensity of freight transport and triggered a so-called "infrastructure overload" effect, evident in the deterioration of road quality, traffic congestion, excessive fuel consumption, and a decline in the efficiency of logistics chains.

The reorientation of freight flows toward road transport has been accompanied by a significant increase in diesel fuel consumption. Based on estimated specific fuel consumption (≈0.035 litres per tonne-km for freight trucks) and an average transport distance of 300 km, the additional load resulting from modal substitution is assessed at approximately ≈800 million litres of diesel fuel annually. This, in turn, translates into an increase in CO_2 emissions of at least 2.1–2.2 million tonnes per year.

According to methodological estimates, the combustion of 1 litre of diesel fuel results in the emission of approximately 2.67 kg CO_2. Consequently, the modal shift in transport of Ukraine's transport sector, particularly within the western logistics corridor. Moreover, emissions from road transport include not only CO_2, but also nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), noise pollution, and soil contamination. This results in a substantial increase in so-called external costs (externalities) – costs that are not reflected in the direct price of freight transport, such as biodiversity loss, time delays and congestion (in monetary terms), emissions of PM_{2-5}/PM_{10}, and ground-level ozone, and public health risks in the affected zones. These costs are ultimately borne by society through increased healthcare expenditures, productivity losses, and environmental degradation.

The estimates are grounded in European Environmental Agency (EEA) methodologies [23], and corresponding guidelines [24], adapted to Ukrainian conditions using cost-per-tonne-kilometre coefficients adjusted for population density and corridor traffic volumes. The data sources include official statistics from Ukraine's State Statistics Service [1], the Ministry of Health, the State Environmental Inspectorate, and national environmental reports for 2020–2021 [27].

According to estimates [25], average external costs of road freight transport in Europe range around $60 per 1,000 tonne-km, whereas, for rail freight, they are approximately $20 per 1,000 tonne-rm. With a 15-percentage-point increase in the share of road transport, Ukraine's annual external costs are projected to rise by an estimated $2.4–2.6 billion. Although this effect does not manifest immediately, it accumulates over time, progressively undermining the social and environmental performance of the logistics sector.

From the perspective of systems analysis, the identified trends generate a negative inertia in logistics development, significantly hindering post-war recovery and highlighting the urgent need for a targeted ecological transformation of Ukraine's transport policy.

Within the scope of this study, special emphasis is placed on a comprehensive assessment of the environmental consequences of military action for transport and logistics networks (TLNs) and infrastructure systems, these include: increased emissions of harmful pollutants into the atmosphere; contamination of water resources; destruction of landscape structures; and disruption of the functional stability of natural ecosystems. To verify the scale and depth of these transformations, the study applies a system of quantitative indicators that enables an evaluation of the extent to which sustainable development principles are integrated into the national transport police framework (Table 2).

At the same time, the economic foundations underpinning environmental transformation have proven vulnerable to disruptive shocks. According to the available data, the period from 2018 to 2023 was marked by a pronounced downward trend in investment volumes directed towards the greening of the transport sector. In 2023, the total amount of funding reached merely UAH 55.9 billion – almost three times less than in 2018 (Table 3).

The most dramatic decline occurred in 2022, when investment dropped to UAH 27.3 billion, a contraction attributable not only to the outbreak of full-scale war but also to the extensive reallocation of resources to support national defence capabilities. Nevertheless, 2023 exhibited signs of partial stabilisation, with investment growth reaching +204.87 percentage points relative to the previous year. Despite this rebound, the institutional and financial capacity of the state to drive ecological modernisation remains constrained.

The war has led not only to an overall reduction in environmental protection investments, but also to profound structural shifts in their allocation across various areas of environmental activity.

The most significant decline was observed in expenditures related to wastewater treatment: in 2023, investment in this area amounted to merely 1.68 percentage points of the 2018 level, reflecting a sixtyfold decrease (Table 4). This dramatic contraction is primarily attributable to the broader degradation of industrial water use systems, the destruction of critical infrastructure – including wastewater treatment facilities – and the chron-

Table 2

Key parameters of the greening TLNs

Decarbonization parameters	Explanation
Share of the transport sector in total GHG emissions	One of the key integrative indicators reflecting the overall environmental footprint of logistics. As of 2021, transport accounted for approximately 13–15 % of total national GHG emissions
Specific CO_2 emissions per 1 t-km (g/t-km)	Includes emissions of CO_2, NO_x, $PM_{2,5}$, and PM_{10} from transport operations. Varies by transport mode (lowest for rail, highest for road). Average for road transport in Ukraine is 180–250 g/t-km
Share of green transport operations	Use of alternative fuels and electric vehicles remains below 3 % of total freight volumes, indicating substantial potential for technological modernization
Energy efficiency of transport fleet	Measures fuel consumption per unit of freight or passenger transport. Fuel consumption gap between old and new vehicles exceeds 40–50 %; over half of Ukraine's freight trucks ate more than 15 years old, contributing to inefficiency and higher emissions
Logistics innovation and process optimization	Route and load optimization, development of multimodal freight, use of intelligent transport systems (ITS). Implementation of environmental performance indicators in logistics to align economic efficiency with sustainability
Infrastructure impact management	Design and construction of transport network and hubs in line with environmental standards (low-carbon materials, solar-powered systems, climate resilience). Mandatory environmental impact assessments (EIA) for construction/reconstruction of logistics facilities
Railway electrification rate	As of 2023, Ukraine had ≈ 45 % of its railway network electrified-below the EU average of 55–60 %. Further expansion is needed, especially in high-volume freight corridors
Environmental investment (as % of GDP)	Reflects the economy's ability to support green transformation. In 2021–2023, capital investments in environmental protection in the T&L sector ranged between 0.03–0.06 % of GDP
Current environmental expenditure in T&L sector	Includes spending on emissions treatment, environmental monitoring, maintenance of eco-modules, and preparation of environmental documentation

Table 3

Capital investment in environmental protection by type of economic activity: "Transport, warehousing, postal and courier services", thousand UAH [1]

Direction of environmental protection activities	2018	2019	2020	2021	2022	2023
Air protection and climate change mitigation	118,510.1	33,034.0	47,832.9	17,023.4	15,078.4	4,557.9
Treatment of wastewater	24,012.2	3,421.7	9,438.1	8,322.2	679.8	404.0
Waste management	17,990.8	10,070.6	3,554.5	3,950.8	1,496.2	7,181.6
Soil, groundwater and surface water protection and rehabilitation	1,577.4	9,845.1	22,957.2	15,108.8	3,242.6	36,548.2
Other environmental activities (noise, biodiversity, radiation safety, R&D, etc.)	6,110.0	7,628.9	6,363.8	10,103.1	6,768.4	7,167.3
Total	168,200.5	64,000.3	90,146.5	54,508.3	27,265.4	55,859.0

Table 4

Current expenditures on environmental protection by type of economic activity: "Transport, warehousing, postal and courier activities", thousand UAH [1]

Direction of environmental protection activities	2018	2019	2020	2021	2022	2023
Air protection and climate change mitigation	–	–	–	36,306.2	35,185.1	89,863.3
Treatment of wastewater	–	–	–	172,089.8	138,369.8	165,377.6
Waste management	–	–	–	197,582.8	206,117.8	287,180.5
Soil, groundwater and surface water protection and rehabilitation	–	–	–	123,687.4	78,807.9	80,350.2
Other environmental activities (noise, biodiversity, radiation safety, R&D, etc.)	–	–	–	172,301.6	66,530.9	68,125.0
Total	574,121.5	754,972.7	717,298.6	701,967.8	525,011.5	690,896.6

ic underfunding of municipal environmental programmes.

A similar downward trend is evident in areas related to air quality protection and climate change mitigation.

In 2023, investments in this domain amounted to a mere 3.85 percentage points of the 2018 level – a twenty-sixfold decrease. This contraction stems from the reallocation of resources towards short-term crisis response measures, the suspension of funding for low-carbon technology deployment projects, and the forced shutdown of numerous industrial enterprises, which temporarily reduced emissions without necessitating additional environmental investment.

At the same time, the largest share of environmental funding in 2023 was allocated to soil and water protection measures, with an extraordinary growth rate of +2,316.99 percentage points, compared to 2018. This surge reflects a n urgent response to the critical need for rehabilitating areas contaminated by heavy metals, petrochemical compounds, and other toxic agents resulting from military operations. Substantial resources were channelled into land reclamation and the conservation of damaged agro-ecosystems.

The resulting investment structure reveals a marked asymmetry in the formation of environmental priorities, whereby strategically essential domains – such as air and wastewater treatment in transport and logistics hubs – remain chronically underfunded. This imbalance poses additional risks to the sustainable recovery of the sector in the post-war period.

In addition to capital investments, current expenditure on environmental protection represents a critical pillar of the ecological transformation of the transport and logistics sector. Such expenditure underpins the functional sustainability of environmental infrastructure and enables the implementation of both preventive and responsive measures to address technogenic threats and environmental challenges – an imperative that has become particularly salient in the context of war, energy constraints, and escalating ecosystem risks.

During the period 2021–2023, current environmental expenditure in the domains of transport, warehousing, postal, and courier services exhibited relative stability, remaining within the range of approximately UAH ≈ 650–700 million per annum. This reflects the sustained prioritisation of ecological concerns in both governmental and corporate police agendas, even under martial law conditions.

Structural analysis reveals that throughout the observed period, the principal category of expenditure remained waste management, with allocations in 2023 exceeding UAH 287 million – constituting approximately 41 percentage points of total environmental spending. These underscores growing awareness of the risks posed by uncontrolled accumulation of transport-related, packaging, and logistics waste, particularly in frontline regions experiencing intensified freight flows and consumption.

Noteworthy, too, is the marked increase in spending on air quality protection and climate change adaptation measures. In 2023, this expenditure reached over UAH 89.9 million – more than double the corresponding figures of preceding years.

Such a trend may indicate a gradual recognition of the critical role that decarbonisation plays in logistics – particularly throughout the modernisation of vehicle fleets, deployment of filtration systems, and initiation of emission reduction programmes in heavy burdened logistic hubs.

Thus, the consistent financing of ongoing environmental measures represents not only an expression of the institutional resilience of the transport sector, but also a crucial mechanism for upholding basic ecological standards during times of crisis.

The second largest expenditure category was wastewater treatment, with allocations exceeding UAH 165 million in 2023. Following a sharp decline in 2022, a renewed upward trend has been observed, which indirectly suggests a systemic adaptation of logistics hubs, an increase in warehousing operations, and the gradual expansion of water remediation initiatives across the transport and processing sectors.

At the same time, other areas of environmental protection – such as noise abatement, biodiversity conservation, radiation safety, and support for scientific research – remain inconsistently financed. During 2022–2023, a clear downward trend in resource allocation for these domains was observed, most likely due to budgetary reallocation in favour of critical infrastructure, reconstruction of damaged facilities, and urgent repair works.

Although the overall level of current environmental expenditure in the sector has remained relatively stable, its internal structure remains asymmetrical and calls for reorientation in line with long-term environmental objectives. Particular attention must be given to areas that are of critical importance under conditions of increasing transport intensity and anthropogenic pressure – specifically, measures to prevent air pollution in transport nodes and the protection of biodiversity in frontline ecological zones.

Moreover, the current structure of environmental expenditure necessitates geospatial optimisation – taking into account the concentration of logistics flows, levels of ecological risk, and the socio-ecological vulnerability of specific territories. The absence of territorially adapted approaches leads to inefficient allocation of funds and exacerbates environmental disparities.

The analysis of environmental financing dynamics over the period 2021–2023 reveals a pronounced asymmetry between capital investments and current expenditures. This imbalance is accompanied by significant fluctuations across constraints but also structural deficiencies in environmental policy within the transport and logistic sector. Among the key issues are persistently low investment levels in emission reduction technologies, the absence of large-scale infrastructure projects aimed at ecological modernisation, and ineffective budget planning – all of which may result in the accumulation of ecologically destructive effects in the medium term (Table 5).

Despite the substantial decline in capital investments targeting core environmental protection areas – such as air quality management, climate change mitigation, and water treatment – current expenditures have demonstrated relative stability and even signs of upward momentum. This may indicate a gradual shift from a purely reactive and adaptive model of environmental governance – one focused on short-term interventions to ensure basic ecological safety under crisis conditions – towards a more structured and potentially strategic framework.

The most illustrative example of this phenomenon is the pronounced imbalance in the domain of air quality protection: while capital investments declined to a bare minimum, current expenditures more than doubled – rising from UAH 35.2 million in 2022 to UAH 89.9 million in 2023 p.

A similar trend was observed in the area of wastewater treatment: despite a sharp reduction in capital funding, current spending showed signs of recovery, which may be interpreted as an attempt to uphold basic ecological safety in logistics hubs through emergency or minimal functional maintenance of drainage and sanitation systems.

The wartime environment has triggered a profound transformation of the financial model underpinning en-

Table 5

Dynamics of environmental project financing, 2021–2023 [1]

Category	Change in capital investment (2023)	Change in current expenditures, 2023
Air protection and climate change mitigation	↓ decreased nearly 26-fold	↑ +UAH 54.7 million compared to 2022
Wastewater treatment	↓ decreased nearly 60-fold	↑ recovered to UAH 165.4 million
Waste management	↓ continued decline	↑ +UAH 89.6 million
Soil, groundwater and surface water protection and rehabilitation	↑ sharp increase to UAH 36.5 billion (highest level)	↑ stable expenditure (≈UAH 80.3 million)

vironmental policy in Ukraine's transport and logistics sector. Funding mechanisms have shifted towards a priority – response regime, whereby financial resources are allocated reactively to urgent interventions aimed at safeguarding a minimum level of ecosystem viability and safety in critical logistical nodes. This has led to a configuration in which long-term capital investment has been drastically curtailed, while the relative share of current expenditures has grown substantially.

While such a financing structure may be justified within the framework of crisis management, it fails to lay the foundations for a long-term ecological transformation of the sector. The prevailing imbalance between maintenance-oriented and modernization-driven expenditures requires urgent rectification. A strategic overhaul of the environmental financing framework is imperative – one grounded in a predictable, institutionally anchored model of sustainable funding. This model must be underpinned by several core elements: state-administered green transition funds, public-private partnership mechanisms, targeted international technical assistance credit lines, and the mandatory integration of environmental standards into the logistics and infrastructure reconstruction processes. Such an approach would reconcile ecological efficiency with economic rationality, enabling the adaptation of TLS to emerging security and climate-related challenges.

In a context of systemic destruction and heightened security threats arising from war, the renewal of transport and logistics infrastructure cannot be reduced to its mere physical reconstruction. Rather, it necessitates a deeper transformation – the one that incorporates environmental priorities, resource resilience, and climate responsibility. This implies a shift toward a new type of network-based organization, combining ecological performance with functional adaptability and technological renewal.

Against the backdrop of current transformational challenges, there arises an imperative to establish a coherent system of strategic benchmarks capable of integrating environmental criteria into the core of transport sector planning, management, and investment. To this end, an indicative assessment model has been developed, structured around key groups of indicators – ranging from carbon intensity to institutional integration and socio-ecological impact. The indicative approach serves two interrelated functions: first, it enables a quantitative diagnosis of the current state of TLS greening: second, it provides a foundation for designing modernization scenarios aimed at achieving concrete objectives within the framework of climate policy, EU standards, and the Green Deal commitments. The implementation of such a system opens up pathways for aligning national transport planning with European approaches, facilitating the strategic allocation of investments toward ecologically impactful priorities, and establishing the necessary preconditions for attracting international financing conditioned by environmental compliance. In the post-war context, this becomes particularly salient, as the reconstruction strategy must not only be technically sound but also structurally transformative.

The development of an effective indicator system for assessing the level of environmental modernization of Ukraine's TLN necessitated the identification of structured indicator clusters that capture both the current ecological status and the dynamics of transition toward sustainable logistics practices. This classification enables a meaningful interpretation of complex multifactorial transformations and facilitates the integration of environmental considerations into the planning, management, and reconstruction processes of transport infrastructure. Moreover, the selection of five indicator groups is grounded in the principles of a systems-based approach, which acknowledges the intricate interdependencies and reciprocal influences among environmental, infrastructural, social, and institutional factors that shape the trajectory of TLN modernization under the conditions of war, economic volatility, and European integration. Each cluster serves as a distinct analytical dimension, allowing for a comprehensive diagnosis of logistics sustainability at both macro and meso-levels. The application of these indicator groups (Table 6) ensures a holistic, systematic, and verifiable evaluation of the ecological status and progress in the domain of sustainable logistics transformation. This approach is fully aligned with contemporary European methodologies for transport policy assessment and provides a robust foundation for adapting Ukraine's logistics sector to the imperatives of climate neutrality and environmental security.

The hierarchical logic of assessment envisages a three-tiered structure of analysis: the national level, focusing on the evaluation of overall progress in the environmental transformation of TLN in accordance with Ukraine's commitments under the Paris Agreement, the European Green Deal, and the National Energy and Climate Plan; the regional level, aimed at identifying territorial disparities in the degree of greening, infrastructure degradation, or investment capacity; the cluster level, dedicated to the localized assessment of specific nodes, border corridors, multimodal clusters, and related components.

A key component lies in the establishment of targeted benchmarks for each indicator block, enabling not only the documentation of the current state but also the definition of concrete quantitative objectives – for example, achieving a minimum 15 % share of electric transport by 2030, or reducing specific CO_2 emissions to below 120 g/t-km. These targets allow for alignment of progress with relevant EU regulations, such as Regulation (EU) 2019/631 (passenger cat emissions), 2019/1242 (heavy-duty vehicles), 2023/1805 (maritime transport), as well as strategic frameworks including the European Green Deal, Fit for 55 Package, and the Sustainable and Smart Mobility Strategy. Furthermore, the indicators serve as a foundation for monitoring compliance with climate goals, including the implementation of the EU Emissions trading System (EU ETS) and the mobilisation of financing through the Connecting Europe Facility (CEF).

Each indicator block is aligned with specific instruments of the EU's green policy framework (Table 7). Indicative target values (benchmarks) have been established for each indicator, grounded in European standards or relevant programme guidelines. The correspondence between each group of indicators and the pertinent policies and regulatory acts enables not only strategic-level monitoring but also the substantiation of funding needs from European financial instruments such as the Connecting Europe Facility (CEF), the LIFE Programme, the EU ETS Innovation Fund, and others.

In the process of Ukraine's environmental transformation of TLN, a critical task is the development and integration into the EU's "green" logistics corridors. Given the need for practical and comparable mechanisms for evaluating the "ecological maturity" of logistics systems, this section introduces a composite metric – *the Environmental Adaptation Index (EAI)* – designed to measure Ukraine's alignment with decarbonization objectives, EU requirements, and the demands of post-war recovery. This index integrates key parameters of ecological efficiency, infrastructure modernization, and socio-environmental pressure within TLNs. Recognizing that baseline normalized values do not always accurately reflect the functional profile of a region, the methodology incorporates corrective adjustments accounting for: the specific structure of transport demand (freight/passenger ration), actual infrastructure utilization (rather than mere availability), multiplier effects (route efficiency, logistical configurations), regional flow dynamics, and urban density.

The distinctive feature of the proposed EAI methodology lies in the synthesis of formal statistical normalization procedures with expert-based adjustments, thereby capturing structural, spatial, and in-

Table 6

Key indicator groups for assessing the level of environmental modernisation of Ukraine's transport and logistics network

No.	Indicator group	Rationale for selection	Indicators
1	Carbon intensity and climate performance indicators	These indicators assess the direst impact of the TLN on greenhouse gas (GHG) emissions, serving as a core criterion for aligning the sector with Ukraine's climate commitments under the Paris agreement and the goals of the European Green Deal. They form the basis for quantitative monitoring of the decarbonization process	Share of the transport sector in total GHG-emissions (%) Specific CO_2, NO_x, $PM_{2,5}$ emissions per tonne-km and passenger-km by transport mode Volume of diesel and petrol consumption in logistics (mln litres/year) Degree of integration into emissions monitoring and reporting systems (IPCC-compliant)
2	Energy efficiency and technological dynamics indicators	These reflect the system's capacity for modernisation under limited investment resources. They demonstrate the fleet renewal rate, penetration of low-carbon technologies, adaptation of alternative fuels, and the energy efficiency of logistics operations	Average age of freight and passenger vehicle fleets Fuel consumption per 100 km for core vehicle categories Share of Euro-5/Euro-6 compliant vehicle Share of electric or hybrid vehicles in logistics operations Electrification rate of railway infrastructure (% of total length)
3	Modal structure and spatial efficiency indicators	This group captures shifts in the transport balance, development of multimodal solutions, and adjustments to logistics configurations due to wartime disruptions. It enables assessment of regional imbalances and utilization of spatial potential, which is critical for reconstruction	Modal split of freight volumes (rail, inland, waterways, air) Share of multimodal freight in total logistics volume (%) Utilisation rate of inland waterway capacity (%) Number of operational logistics terminals, multimodal hubs, and transshipment platforms Density of logistics nodes per 1,000 $км^2$
4	Institutional capacity and regulatory integration indicator	These reflect the readiness of national transport policy to implement EU environmental standards, availability of legal frameworks, monitoring mechanisms, and green financing architecture. They are essential for strategic planning, securing international support, and complying with EU regulatory requirements	Existence of national programmes for greening TLN Public and private funding volumes for green logistics projects Compliance rate with EU decarbonization regulations (% implemented) Availability of environmental certification systems and sustainability criteria for logistics operations
5	Socio-environmental impact and externalities indicators	Logistics must also be assessed by its effects on public health, quality of life, and environmental degradation. This group identifies externalized costs and integrates them into sustainable assessments with a focus on social justice and long-term ecological risks	External cost per 1 t-km (based on CT Delft methodology) Average air pollution in logistics hubs (NO_2, $PM_{2,5}$, PM_{10}) Area of degraded land along transport corridors (ha) Prevalence of noise exposure and public complaints in logistics cluster zones

stitutional dimensions not directly reflected in standard indicators.

In contrast to conventional approaches that rely solely on statistical data and mechanical aggregation of metrics, the proposed methodology incorporates:

- asymmetry of logistics flows – for instance, the decline in freight traffic in the eastern regions due to military operations of the re-routing of cargo through western corridors;

- functional specialization of regions, which may not always be captured in quantitative indicators but has a substantial impact on environmental load. A case in point is the city of Kyiv, which functions primarily as a passenger hub with a limited logistics component;

- institutional capacity for implementing environmental solutions – assessed through the presence of strategies, projects, and programmes, even in the absence of a fully developed statistical framework;

- spatial and infrastructure constraints, although not always quantifiable, exert an indirect yet significant influence on key performance parameters of transport and logistics systems – reducing energy efficiency, limiting multimodality, and amplifying externalities such as emissions, noise pollution, and congestion.

For selected regions, adjustment coefficients within an expert-approved range (±5–10 %) of the normalized value were applied, allowing the model to account for the actual ecological impact of logistics activity rather than relying solely on formal indicators.

Accordingly, the Environmental Adaptation Indes (EAI) functions as a hybrid assessment system, integrating the quantitative objectivity of normalized indicators, the quantitative expert interpretation of regional specificities, and the institutional-spatial evaluation of logistic systems.

This multifaceted integration enhances the precision and relevance of the index for informed policy and management decisions (Table 8).

This approach delivers greater sensitivity to the contextual realities of Ukraine's post-war infrastructure development, surpassing the adaptability of traditional European models such as TERM (Transport and environment reporting mechanism) and SMI (Sustainable mobility indicators), which are tailored to conditions of systemic stability.

A full EAI calculation was carried out for six regions – Lviv, Kyiv, Kharkiv, Odesa, Zaporizhzhia, and Dnipropetrovsk – based on normalised datasets refined through expert corrections. The results are presented in Table 9.

The distinguishing feature of the proposed EAI methodology lies in its ability to merge formal statistical normalisation procedure with expert-driven adjust-

Table 7

Comparability of Ukraine's indicative assessment system for TLM modernisation with EU green policy instruments

Indicator group	Target by 2030	Corresponding EU instrument
Carbon intensity and climate performance	≤ 50 g/t-km CO_2	Regulation (EU) 2019/631, European Green Deal
Energy efficiency and technological dynamics	≥ 40 % of vehicles < 5 years old; ≥ 65 % freight transport via electric traction; ≥ 15 % electric vehicles in logistics	Fit for 55, EU Energy Efficiency Directive, TEN-T Regulation, CEF, EU Battery Regulation
Modal structure and spatial efficiency	≥ 35 % share of rail and inland waterways; ≥ 3 % of logistics hubs per region as multimodal	Sustainable Mobility Strategy, TEN-T, Connecting Europe Facility
Institutional capacity and regulatory integration	Presence of regional decarbonization plan for the logistics network	CEF accession mechanism, EU integration roadmap
Socio-environmental impact and externalities	Reduction of external costs by at least 20 % from 2020 levels	EU ETS, polluter pays principles, EU External Cost Guidelines

Table 8

Multi-indicator approach for normalizing baseline parameters

Indicator	Notation	Expected trend	Normalisation method
CO_2 emissions per tonne-km	CO_2	↓ Lower is better	Inverse
Share of logistics electrification	ELEC	↑ Higher is better	Direct
Multimodality level	MULTU	↑ Higher is better	Direct
Energy efficiency (t-k, per litre)	ENEFF	↑ Higher is better	Direct
External costs (USD per t-km)	EXT	↓ Lower is better	Inverse

Table 9

Indicative table of the environmental adaptation level of Ukraine's regional transport infrastructure

Region	CO_2	ELECT	MULTU	ENEFF	EXT	EAI
Lviv	0.38	0.65	0.60	0.58	0.36	**0.57**
Kyiv	0.42	0.78	0.64	0.59	0.33	**0.55**
Kharkiv	0.55	0.63	0.56	0.50	0.40	**0.53**
Zaporizhzhia	0.58	0.62	0.54	0.50	0.42	**0.52**
Odesa	0.49	0.58	0.52	0.49	0.44	**0.51**
Dnipropetrovsk	0.52	0.60	0.51	0.48	0.39	**0.50**

ments that incorporate structural, spatial, and institutional factors not captured by conventional metrics.

Although regional differences in EAI values are relatively modest (≈0.50–0.57), they reveal clear scope for targeted interventions. The observed divergence reflects underlying structural disparities in the ecological maturity of logistics systems, offering insight into which regions should be prioritised for support, scaling-up, or restructuring.

Lviv and Kyiv regions emerge as frontrunners, demonstrating advanced environmental adaptation. Kharkiv regions, despite the impact of military operations, maintains a moderate level of adaptation, supporting it is well-positioned for pilot recovery initiatives. The most significant untapped potential lies in the Dnipropetrovsk, Zaporizhzhia, and Odesa regions, which require accelerated integration into green modernisation processes, particularly in the areas of energy efficiency, emissions reduction, and multimodal infrastructure development.

All three regions possess significant logistical assets; however, they are markedly affected by the consequences of military conflict and a shortage of green investment. Accordingly, the proposed Environmental Adaptation Index (EIA) system serves not only as a diagnostic tool but also as a strategic and operational framework. It provides a conceptual foundation for shaping a regional differentiated policy of greening TLNs. The implementation of the EAI makes it possible to: identify regions with critical levels of environmental pressure; justify investment prioritisation, and optimise infrastructure recovery mechanisms in line with principles of environmental justice. Moreover, the EAI may be employed as a regular monitoring and evaluation instrument, enhancing the transparency and effectiveness of policy actions in both the transport sector and environmental protection.

Given the profound transformation of Ukraine's TLNs under the weight of recent large-scale challenges, there is a growing need for tools that not only assess regional ecological readiness strategically but also enable targeted management of the environmental performance of individual logistics corridors. In this context, a specialised instrument is introduced – the Environmental Corridor Logistic Index System (ECOLOGIS) – designed to function as an analytical basis for short- and medium-term environmental planning in the transport sector (Table 10).

Unlike the EAI, which operates as a high-level strategic indicator at the regional scale, ECOLOGIS is focused on the operational diagnosis of logistics flows and the planning of environmental modernisation along specific transport axes.

The Green corridor rating system has developed as an operational-level analytical tool that enables the evaluation of the environmental performance of transport routes based on a set of quantitative indicators. The determination of weighting coefficients for the ECOLOGIS indicators is grounded in an expert assessment methodology that takes into account three principles criteria: a) regulatory relevance of the indicator; b) manageability, i.e. the potential for policy or administrative intervention to influence the indicator; c) temporal dynamics of the effects associated with the indicator. To ensure objectivity, the expert assessment involved 12 specialists, evenly split between academic experts in transport and environmental economics (6 participants), and practitioners with managerial experience in transport infrastructure (6 participants). The pairwise comparison procedure was conducted using the Saaty scale (1–9). The Consistence Index (CI) of the evaluations was calculated at 0.08, which reflects an acceptable level of internal logical consistency in expert judgments. The resulting weight were averaged and incorporated into the final version of the ECOLOGIS index.

All indicators were normalised within the range [0; 1], where 1 denotes the best environmental performance. For indicators such as CO_2 emissions and external costs (EXT), inverse normalisation was applied. The composite Environmental Corridor Logistic Index (ECOLOGIS) was calculated using the following formula

$$\text{ECOLOGIS} = 0.30 \cdot \text{CO}_2\text{\_inv} + 0.20 \cdot \text{ELEC} +$$
$$+ 0.20 \cdot \text{MULTI} + 0.15 \cdot \text{ENEFF} + 0.15 \cdot \text{EXT\_inv}$$

This approach enables the harmonisation of indicators that differ in nature and scale within a unified metric framework, thereby ensuring the objective comparability of transport routes and facilitating the identification of spatial environmental priorities. The ECOLOGIS-based assessments of selected logistics corridors – Western, Central-1, Central-2, Danube, and Eastern – revealed significant disparities in environmental performance. The resulting ranking of corridors according to their composite score provided a clear basis for identifying priority directions for the sustainable development of Ukraine's transport infrastructure in the context of post-war recovery (Table 11).

However, the effective implementation of the green logistics concept requires not only the internal optimisation of routes but also their strategic integration into the Trans-European and Pan-European transport systems.

In this context, a clear alignment has been established between Ukraine's Network (TEN-T) and the Pan-European Corridors, enabling the strategic reorientation of network development in accordance with the standards of the European Green Deal. For example, the Western Logistics Corridor (Lviv – Uzhhorod – Chop) operates as a cross-border extension of Pan-European Corridor V, including its eastern Mediterranean

Table 10

Matrix of strategic relevance of indicators for the environmental ranking of Ukraine's logistics routes

indicator	Regulatory significance	Managerial leverage	Temporal horizon	Weight, %
CO_2 emissions	Very high	High	Short-term	30
Electrification	High	High	Medium-term	20
Multimodality	High	Medium	Medium/long term	20
Energy efficiency	Moderate	Medium	Long-term	15
External costs	High	Limited	Long-term	15

Table 11

Comparative analysis of the environmental performance of Ukraine's National logistics routes

Corridor	CO_2_inv.	ELEC	MULTI	ENEFF	EXT _inv.	ECOLOGIS	Comment
Western	0.66	0.7	0.72	0.6	0.65	0.661	Highest level of multimodality and CO_2 efficiency; scaling up of multimodal platforms is recommended
Central-1	0.58	0.74	0.68	9.55	0.59	0.629	High level of electrification; requires optimisation of modal structure and hub modernisation
Central-2	0.61	0.71	0.66	0.59	0.61	0.640	Balanced indicators; recommended to increase multimodality and promote sustainable routes
Danube	0.61	0.67	0.64	0.57	0.62	0.637	Well-developed inland waterways, high CO_2 efficiency; strong potential for multimodal growth
Eastern	0.48	0.53	0.52	0.48	0.45	0.497	Low energy efficiency and CO_2 index; infrastructure upgrade and green reorientation are needed

branch, thereby providing a sustainable logistical link with the transport systems of Slovakia and Hungary.

The corridors included in the analysis exhibit varying degrees of readiness for environmental transformation. The Western and Danube routes are the most suitable for immediate green investment, while the Central corridors require functional enhancement, and the Eastern corridor demands systemic reconstruction. The spatial configuration and environmental performance of national logistics corridors must adhere to the core principles of the TEN-T network – namely, integration into the European transport area, support for decarbonisation, promotion of multimodality, enhanced energy efficiency, and infrastructure compatibility with EU technical standards. Such alignment is an essential precondition for Ukraine's full-fledged inclusion in the TEN-T framework as a strategic partner, on line with the objectives of the European Green Deal.

The proposed analytical system for assessing the environmental condition and potential of Ukraine's TLNs is based on the conceptual integration of two complementary instruments – the Environmental Adaptation Index (EAI) and the Environmental Corridor Logistic Index System (ECOLOGIS)/together, they form a dual-component analytical platform capable of supporting systemic strategic planning for the decarbonisation on the transport sector. The EAI provides a macro-level assessment of regional environmental capacity, while ECPLOGIS capture the operational and spatial realisation of environmental performance within transport flows. Their synergy establishes the foundation for a new governance paradigm, oriented towards Ukraine's integration into the trans-European Transport Network (TEN-T), the implementation of the European Green Deal principles, and the strengthening of climate accountability within national transport police.

The synergistic application of EAI and ECOLOGIS delivers a robust methodological basis for comprehensive environmental governance of Ukraine's TLNs, enabling: the formulation of strategic planning for sustainable recovery; the establishment of investment and budgetary support priorities; the design of regional differentiated policies based on environmental risk profiling; the development of regional ecological resilience profiles (so-called "green passports"); the adaptation of national transport policy to the requirements of the European Green Deal and TEN-T framework; and the introduction of regular monitoring mechanisms to assess the effectiveness of green transport initiatives.

Conclusions. The conducted study confirms that the full-scale war has acted as a catalyst for the systemic transformation of Ukraine's TLNs, fundamentally altering the spatial structure of logistic flows, disrupting long-established infrastructure linkages, intensifying energy vulnerability, and exacerbating interregional disparities. Under these conditions, the structural-ecological profile of Ukraine's TLNs has undergone significant distortion: route fragmentation has increased; the modal structure is shifting markedly towards road transport; this shift has led to a rise in specific CO_2 emissions; ecosystem impacts have become more complex, and external environmental costs have escalated, now exceeding USD 11 billion annually. In parallel, the research revealed pronounced imbalances in the resource provision for greening efforts – both territorially and in terms of the structure of financial flows.

In response to these challenges, a system for comprehensive assessment of the environmental adaptation level of TLNs to sustainable development requirements has been developed. This system is based on the construction of the Environmental Adaptation Index (EAI). Its verification has demonstrated a significant degree of interregional differentiation in environmental capacity, highlighting the urgent need for a targeted financing policy aimed at reducing spatial disparities in the ecological transformation of transport infrastructure.

To straighten the spatial dimension of environmental planning within the framework of national logistics policy, a new applied instrument is proposed – the Green Corridor Rating System (ECOLOGIS), implemented through an original composite index. The application (the Danube, Central, and Western corridors) and those directions demonstrating critically low performance, which require urgent reconstruction of their development scenarios. A preliminary test of the structural robustness of the ranking under a modest variation of weight coefficients (± 10 %) revealed relative inertia in the positions of key indicators. A full-scale sensitivity analysis of the model – including Monte Carlo simulations and scenario modelling (e.g., changes in electrification, multimodality, and external costs) – is scheduled as a separate stage of future research to evaluate the stability of the ranking system.

In summary, the greening of TLNs in wartime Ukraine is not approached as a reactive measure to crisis conditions, but rather as a strategic vector of structural and functional rethinking of logistics – positioning it as a cornerstone of economic recovery. The formation of a new green transport framework must rely on verified analytical assessment models, which not only reflect the current state but also enable the projection of adaptive development scenarios, tailored to the sectoral, institutional and resource characteristics of each region. Given the space limitation of this article, an in-depth case analysis of individual logistics corridors and a comprehensive stress test of the ECOLOGIS model under various scenarios are planned as the next phase of research. At the same time, the practical implementation of the models such as EAI and ECOLOGIS must account for a range of potential risks, including: limited availability of statistical and operational data; constraints in financing green projects; institutional inertia; and low levels of data digitalisation at the subnational level. To mitigate these risks, it is essential to establish an open-access monitoring system, involve regional governance bodies, and ensure coordination with international donors to secure early-stage funding. The proposed model should thus be regarded both as a robust evaluation tool and a practical guide for strategic environmental planning in the post-war reconstruction of Ukraine's transport system.

References.

1. State Statistics Service of Ukraine (n.d.). Retrieved from https://www.ukrstat.gov.ua/
2. *A Guide to Integrating Transport into Nationally Determined Contributions (NDCs)* (2024). ITF. Retrieved from https://www.itf-oecd.org/sites/default/files/docs/transport-ndc-guide.pdf
3. Verkhovna Rada of Ukraine (2015). *Paryzka uhoda* Retrieved from https://zakon.rada.gov.ua/laws/show/995_l61#Text
4. *Sustainable transport, sustainable development* (2021). UN. Retrieved from https://sdgs.un.org/sites/default/files/2021-10/Transportation%20Report%202021_FullReport_Digital.pdf
5. World bank group (2023). *Unlocking Green Logistics for Development*. Retrieved from https://documents1.worldbank.org/curated/en/099102423134510604/pdf/P1748631851e145c112a61483d1abea15143644fd1e1.pdf
6. UNECE (n.d.) *Climate Change and Sustainable Transport*. Retrieved from https://unece.org/transport/climate-change-and-sustainable-transport
7. ITF (2023). *Transport System Resilience*. Retrieved from https://www.itf-oecd.org/node/28344
8. EC (n.d.) *The European Green Deal*. Retrieved from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
9. EC (2021). *The Sustainable and Smart Mobility Strategy of the European Commission – A critical assessment* Retrieved from https://www.changing-transport.org/wp-content/uploads/EU-Mobility-Strategy.pdf
10. World bank group (2015). *Moving Toward Climate-Resilient Transport* Retrieved from https://thedocs.worldbank.org/en/doc/326861449253395299-0190022015/render/WorldBankPublication-ResilientTransport.pdf
11. UN, UNCTAD (2018). *Sustainable Freight Transport in Support of the 2030 Agenda for Sustainable Development* Retrieved from https://unctad.org/system/files/official-document/cimem7d17_en.pdf
12. UNESCAP (2013). *Intergovernmental Agreement on Dry Ports* Retrieved from https://www.unescap.org/resources/intergovernmental-agreement-dry-ports
13. IENE/ICOET (2020). *A Global Strategy for Ecological Sustainable Transport and other Linear Infrastructure* Retrieved from https://www.iene.info/content/uploads/2020Dec_TheGlobalStrategy90899.pdf
14. ITF (2023). *Measuring New Mobility. Definitions, Indicators, Data Collection* Retrieved from https://www.itf-oecd.org/sites/default/files/docs/measuring-new-mobility-definitions-indicators-data.pdf
15. Vovk, Yu., Vovk, I., Plekan, U., Tson, O., & Oleskyuk, V. (2025). Sustainable and smart logistic centers: Challenges and opportunities for Ukraine's transport system. *Journal of Sustainable Development of Transport and Logistic*, *10*(1), 116-124. https://doi.org/10.14254/jsdtl.2025.10-1.8
16. Benoliel, M., Ferreira, P., & Silva, C. (2023). Green urban railway stations: A methodology to assess and improve sustainability. *Transportation Research Procedia*, *72*, 1515-1522. https://doi.org/10.1016/j.trpro.2023.11.618
17. Hristov, I., & Chirico, A. (2019). The role of sustainability key performance indicators (KPIs) in Implementing Sustainable Strategies. *Sustainability*, *11*(20), 5742. https://doi.org/10.3390/su11205742
18. Palyvoda, O. M. (2023). Growth Strategies for Transport Enterprises of Ukraine in the Conditions of European Integration and War. *Business Inform*, *8*, 185-192. https://doi.org/10.32983/2222-4459-2023-8-185-192
19. Marchenko, O., & Hrabin, O. (2024). Green and digital transformation of the Ukrainian economy: priorities for post-war recovery, *Economy and Society*, *59*. https://doi.org/10.32782/2524-0072/2024-59-173
20. Martseniuk, L., & Shipov, V. (2024). Directions of sustainable development of rail transport in Ukraine. *Scientific bulletin of Dnipro state University of internal affairs*, *2*, 153-163. https://doi.org/10.31733/2078-3566-2024-2-153-163
21. Voronkova, V., Nikitenko, V., & Metelenko, N. (2025). "Green" digital transformation as a driver of sustainable regional development in post-war recovery. *Educational Discourse*, *52*(1-2), 22-30. https://doi.org/10.33930/ed.2019.5007.52(1-2)-3
22. European Commission (n.d.). *Transport and Green Deal*. Retrieved from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/transport-and-green-deal_en
23. EU (n.d.). *Handbook on the external costs of transport*. Retrieved from https://op.europa.eu/en/publication-detail/-/publication/9781f65f-8448-11ea-bf12-01aa75ed71a1
24. EEA (2021). *Transport and environment report 2020 – Train or plane*? Retrieved from https://www.eea.europa.eu/en/analysis/publications/transport-and-environment-report-2020
25. EEA (n.d.). *Transport and Environment reporting Mechanism* (TERM) publications. Retrieved from https://www.eea.europa.eu/en/topics/in-depth/transport-and-mobility/transport-and-environment-reporting-mechanism-term
26. Nykyforuk, O., & Ilchenko, S. (2025). Legal foundations of the environmental transformation of Ukraine's transport sector in the context of European integration. *Economics and Law, 2*, 85-100. https://doi.org/10.15407/econlaw.2025.02.085
27. Ministry of Environmental protection and Natural resources of Ukraine (n.d.). *National Environmental Reports of Ukraine* Retrieved from https://mepr.gov.ua/diyalnist/napryamky/ekologichnyj-monitoryng/natsionalni-dopovidi-pro-stan-navkolyshnogo-pryrodnogo-seredovyshha-v-ukrayini/

Індикативна модель еколого-адаптивної модернізації транспортно-логістичної мережі України

С. В. Ільченко

Державна установа «Інститут економіки та прогнозування НАН України», м. Київ, Україна

* Автор-кореспондент e-mail: ilchenko.svit@gmail.com

Мета. Сформувати науково обґрунтовану індикативну модель еколого-адаптивної модернізації транспортно-логістичної мережі (ТЛМ) України та оцінити рівень її екологічної адаптації до вимог сталого розвитку з урахуванням просторово-структурних трансформацій ТЛМ і сучасних екологічних викликів.

Методика. У досліджені застосовано індикативний підхід до оцінки екологічної адаптації ТЛМ України, що базується на побудові мультиіндикаторної моделі із використанням групи показників: рівень викидів CO_2 у транспортному секторі, ступінь електрифікації транспортних засобів, розвиток мультимодальних перевезень, енергоефективність транспортної інфраструктури й обсяг зовнішніх екологічних витрат. На основі нормалізованих значень побудовано індекс екологічної адаптації (EAI) для окремих регіонів та інтегральний «зелений» рейтинг (ECOLOGIS) для логістичних коридорів України. Методика включає також просторовий аналіз, кластеризацію регіонів за рівнем адаптації й оцінку структурних змін у модальній логістиці під впливом війни.

Результати. Проведена регіональна оцінка екологічної адаптації ТЛМ України, що дозволило виокремити області з високим, середнім і низьким рівнем адаптації до викликів сталого розвитку. Встановлено, що найбільший екологічний потенціал зосереджено у логістичних коридорах із переважанням електрифікованих і мультимодальних перевезень. Виявлені суттєві просторові диспропорції в еколого-структурному профілі регіонів, що визначає пріоритети для подальшої модернізації інфраструктури.

Наукова новизна. Полягає у розробці індикативної моделі еколого-адаптивної модернізації ТЛМ України, індексу екологічної адаптації й системи оцінювання ефективності логістичних коридорів ECOLOGIS для просторової діагностики й визначення пріоритетів сталого розвитку інфраструктури у повоєнний період.

Практична значимість. Полягає у створенні аналітичного інструментарію для оцінювання екологічної адаптації ТЛМ до вимог сталого розвитку й викликів підвищеного екологічного навантаження в умовах війни. Запропоновані інструменти дозволяють обґрунтувати пріоритети модернізації, оптимізувати просторове планування та підтримувати прийняття управлінських рішень у сфері екологізації транспортної інфраструктури на національному й регіональному рівнях.

Ключові слова: *транспортно-логістична мережа, екологічна адаптація, сталий розвиток, просторово-структурна трансформація*

The manuscript was submitted 17.06.25.