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# SCENARIO MODELLING OF INVESTMENT NEEDS FOR THE RESILIENT RECOVERY OF UKRAINE'S CRITICAL INFRASTRUCTURE: STRATEGIC PATHWAYS UNDER WARTIME AND POST-WAR RISKS

***Nataliia Trushkina. "Scenario Modelling of Investment Needs for the Resilient Recovery of Ukraine's Critical Infrastructure: Strategic Pathways under Wartime and Post-War Risks".*** *The article substantiates a scenario-based approach to assessing investment needs for the resilient recovery of Ukraine's critical infrastructure under wartime and post-war risks. The empirical basis of the study comprises the results of RDNA1–RDNA5, which were used to systematise the dynamics of direct damage, economic losses, and recovery needs and to construct an analytical infrastructure block. The methodological framework combines systems and comparative analysis, scenario and simulation modelling, and multi-criteria assessment. Investment needs are treated as a dynamic variable that changes under the influence of new and repeated damage, project implementation rates, financial and institutional constraints, the selected recovery standard, and the capacity of investments to reduce future risks. Four strategic pathways are proposed – minimal-recovery, functional-adaptive, Build Back Better modernisation, and resilience-transformational – together with three types of risk environment, integrated into a scenario matrix. Under the specified scenario assumptions and a baseline value of USD 218.9 billion, the estimated residual needs in 2030 amount to USD 253.8, 197.9, 171.1, and 142.4 billion, respectively. The findings demonstrate that minimising initial capital expenditure is not equivalent to minimising long-term investment needs and systemic risk. The scientific novelty lies in distinguishing strategic choice from the external risk environment, interpreting investment needs dynamically, and linking resource constraints with functional outcomes. The practical significance of the proposed approach lies in its applicability to scenario testing, prioritisation, and portfolio formation of critical infrastructure projects*

***Keywords****:* critical infrastructure, resilient recovery, investment needs, scenario modelling, strategic pathways, wartime risks, post-war recovery, Build Back Better, investment prioritisation, external threats

***Наталія Трушкіна. "Сценарне моделювання інвестиційних потреб для резильєнтного відновлення критичної інфраструктури України: стратегічні траєкторії в умовах воєнних і***

***повоєнних ризиків".*** *У статті обґрунтовано сценарний підхід до оцінювання інвестиційних потреб для резильєнтного відновлення критичної інфраструктури України в умовах воєнних і повоєнних ризиків. Емпіричну основу дослідження становлять результати RDNA1–RDNA5, за якими систематизовано динаміку прямої шкоди, економічних втрат і потреб у відновленні та сформовано аналітичний інфраструктурний блок. Методичний інструментарій поєднує системний і порівняльний аналіз, сценарне та імітаційне моделювання, багатокритеріальне оцінювання. Інвестиційні потреби розглянуто як динамічну величину, що змінюється під впливом нової і повторної шкоди, темпів реалізації проєктів, фінансових та інституційних обмежень, обраного стандарту відновлення і здатності інвестицій знижувати майбутній ризик. Запропоновано чотири стратегічні траєкторії – мінімально-відновну, функціонально-адаптивну, модернізаційну Build Back Better та резильєнтно-трансформаційну – і три типи ризикового середовища, поєднані у сценарну матрицю. За заданих сценарних припущень і базового значення 218,9 млрд дол. США розрахунковий залишок потреб у 2030 р. становить відповідно 253,8; 197,9; 171,1 і 142,4 млрд дол. Встановлено, що мінімізація початкових капітальних витрат не тотожна мінімізації довгострокових потреб і системного ризику. Наукова новизна полягає у розмежуванні стратегічного вибору та зовнішнього ризикового середовища, динамічному трактуванні інвестиційних потреб і поєднанні ресурсних обмежень із функціональним результатом. Практичне значення підходу полягає у можливості його використання для сценарного тестування, пріоритизації та формування портфеля проєктів критичної інфраструктури.*

***Ключові слова:*** критична інфраструктура, резильєнтне відновлення, інвестиційні потреби, сценарне моделювання, стратегічні траєкторії, воєнні ризики, повоєнне відновлення, Build Back Better, інвестиційна пріоритизація, зовнішні загрози.

**Introduction.** The full-scale war has changed not only the scale of destruction inflicted on Ukraine's critical infrastructure but also the underlying economic logic of its recovery. Under the conventional post-crisis model, damage assessment, needs estimation, and the development of reconstruction programmes generally take place after the destructive event has ended. The situation in Ukraine is fundamentally different. Recovery activities are being carried out while the military threat persists, meaning that already repaired facilities may suffer repeated damage, the spatial distribution of population and economic activity continues to change, the cost of equipment and construction works rises, logistics chains become increasingly complicated, and requirements for physical, technological, and digital security are continuously tightened. As a result, recovery can no longer be regarded as a one-time reconstruction of lost assets. Instead, it becomes a prolonged process of managing infrastructure functionality, vulnerability, and investment needs under conditions of uncertainty [1–5].

The quantitative parameters of reconstruction confirm the systemic nature of this challenge. According to the five consecutive Rapid Damage and Needs Assessments, from RDNA1 to RDNA5, direct damage to Ukraine increased from 97.4 billion to 195.1 billion United States dollars, economic losses from 252.0 billion to 666.7 billion United States dollars, and ten-year recovery needs from 348.5 billion to 587.7 billion United States dollars [6–11]. At the same time, economic losses accumulated substantially faster than physical damage. Between 2022 and 2025, economic losses increased by 164.6 percent, compared with an increase of 100.3 percent in direct damage, while the ratio of losses to damage rose to 3.42. This indicates that the economic consequences of infrastructure destruction arise not only at the moment when an asset is physically damaged. A considerable share of these consequences accumulates throughout the period in which critical functions remain disrupted, taking the form of foregone revenues, additional operating costs, shortages of essential services, reduced production activity, and secondary effects transmitted across interdependent sectors.

An important structural feature of the recovery process is the increasing role of the infrastructure component. For analytical purposes, an infrastructure block was constructed on the basis of the Rapid Damage and Needs Assessments, comprising energy and extractive industries, transport, telecommunications and digital infrastructure, water supply and sanitation, and municipal services. The estimated recovery needs of this block increased from 98.9 billion United States dollars in RDNA1 to 218.9 billion United States dollars in RDNA5 [6–11]. It accounted for approximately 50.2 percent of the overall increase in recovery needs between the first and fifth assessments, and for 77.2 percent of the increase between RDNA4 and RDNA5. At the same time, this analytical aggregate should not be equated with Ukraine's legally defined critical infrastructure system. Its analytical value lies primarily in its ability to trace the dynamics of sectors whose functioning directly determines the continuity of basic services and the resilience of other components of the economic system. For this reason, allocating resources solely according to sectoral affiliation or the scale of physical destruction is insufficient. Investment decisions must also take into account the criticality of the function performed, the number of dependent users, the possibility of substitution, the facility's position within the network, and its potential to trigger cascading failures.

This leads to a distinction that is fundamental to investment planning: direct damage, recovery needs, and the amount of investment actually required are not equivalent concepts. The value of a damaged asset reflects the scale of the physical loss, but it does not automatically determine either the cost of restoring the critical function or the target configuration of the recovered system. An estimated recovery need, in turn, is not equivalent to the volume of financing that can be mobilised and effectively utilised within a given period. Likewise, the formal completion of construction or repair works does not necessarily mean that the required level of functionality and resilience has been achieved [1; 6–14]. This distinction is particularly pronounced in network infrastructure. Physical damage of the same monetary value may produce substantially different consequences depending on the systemic role of the damaged node, the availability of alternative routes and reserve capacities, the duration of disruption, and the possibility of rapid substitution. The initial capital cost of a project therefore cannot, by itself, serve as a sufficient criterion for determining its investment viability.

A further constraint arises from the gap between the scale of long-term needs and the actual capacity to transform financial resources into completed projects that deliver functional outcomes. The problem extends well beyond a shortage of financing. Investment feasibility depends on the availability of a sufficiently prepared project pipeline, feasibility studies and design documentation, secure access to infrastructure facilities, contractor and production capacity, access to equipment, procurement timelines, institutional coordination, and the capacity to operate and maintain newly created or restored facilities. Consequently, the path from total estimated recovery needs to the actual restoration of a critical function involves not one but several successive gaps: financial, project preparation, implementation, technical, functional, and resilience gaps. Treating these gaps as a single issue creates the misleading impression that mobilising the required amount of funding automatically means that recovery has been completed.

The choice of the infrastructure condition that investment is intended to achieve is equally important. Restoring pre-war technical characteristics may be justified when the immediate objective is to return specific functions to operation, but it is not always rational from a life-cycle perspective. If reconstruction reproduces the previous territorial concentration of capacities, technological obsolescence, insufficient interchangeability, or single points of failure, it simultaneously preserves some of the vulnerabilities embedded in the pre-existing system. An alternative approach is to incorporate modernisation, physical and digital protection, redundancy, decentralisation, autonomy, spatial dispersion of critical nodes, and improved maintainability into investment decisions. This is precisely where the difference between restoring an asset and ensuring the resilient recovery of a system becomes apparent. Higher expenditure at the initial stage may be economically justified if it shortens the duration of future disruptions, reduces the scale of repeated damage, and lowers expected losses over the infrastructure life cycle [2–4; 7–11].

The challenge of financing critical infrastructure therefore has not only a quantitative dimension but also structural and temporal dimensions. The key issue becomes the choice among different ways of allocating scarce resources: rapidly replacing damaged assets; prioritising the restoration of critical functions through temporary, mobile, and reserve solutions; undertaking technological modernisation in line with new standards; or pursuing a deeper transformation of the infrastructure system aimed at reducing future risk. These alternatives differ not only in their initial costs but also in implementation timelines, financing requirements, their effects on system functionality, and their capacity to prevent the renewed accumulation of recovery needs.

The need to make such choices will persist even after the intensity of direct hostilities declines. A post-war environment will not automatically imply a transition to risk-free reconstruction. Accumulated damage and the territorial unevenness of destruction will be compounded by limited availability of long-term capital, changes in the spatial distribution of population and economic activity, shortages of certain types of equipment and specialised expertise, cyber and technological threats, and the need to align new infrastructure with the requirements of European integration, decarbonisation, energy efficiency, and resource efficiency. Accordingly, decisions taken under the pressure of urgent wartime needs will have long-term consequences. They may either create the foundation for structural modernisation or lock the system into technological and spatial configurations whose subsequent modification would require substantial additional expenditure.

Against this background, the scientific problem lies in the need to reconcile the dynamic formation of investment needs with the choice of a strategic trajectory for critical infrastructure recovery in a changing risk environment. A static estimate of reconstruction costs does not capture the fact that future needs depend on new and repeated damage, the pace of project implementation, the level of available financing, the selected recovery standard, and the capacity of completed investments to reduce subsequent vulnerability. Nor does such an estimate allow the economic consequences of alternative decisions to be compared adequately, ranging from minimum repair to functional adaptation, technological modernisation, and the resilient transformation of the infrastructure system.

Investment justification for critical infrastructure therefore requires a shift away from searching for a single "cost of reconstruction" towards analysing a range of possible recovery trajectories. Each trajectory is shaped by a particular combination of the external risk environment, the target condition of the infrastructure, the pace of project implementation, resource constraints, and the expected effect of risk reduction. Scenario modelling within this framework makes it possible to assess not only the amount of investment required but also the consequences of choosing different recovery models over time. The rationality of an investment decision is therefore determined not by the minimisation of initial expenditure as such, but by the relationship between investment, function, time, risk, and avoided losses. This relationship makes it possible to connect the cost of reconstruction with its ultimate outcome: the capacity of critical infrastructure to sustain vital functions and adapt to wartime and post-war risks.

**Analysis of recent research and publications.** Scientific approaches to the study of critical infrastructure have undergone a marked evolution over recent decades. While earlier research focused primarily on the physical protection of individual assets and on minimising the probability of their damage, contemporary scholarship increasingly relies on a systemic understanding of infrastructure as a set of interconnected networks, functions, and services whose disruption may generate much broader economic and social consequences. At the same time, international and Ukrainian researchers have developed this understanding under different institutional and security conditions, which has resulted in certain differences in the focus of analysis, methodological tools, and the interpretation of recovery priorities.

In the international literature, the resilience-oriented approach has become one of the leading perspectives. A. Mentges et al. [1] demonstrate that the meaning of resilience is context-dependent and that no universal interpretation can be applied equally to different types of critical infrastructure. W. Liu et al. [15] understand infrastructure resilience as the capacity of a system to prepare for disruptive events, absorb their consequences, restore its functioning, and adapt to changed conditions. The systematic reviews by M. Sathurshan et al. [16] and B. Rathnayaka et al. [17] confirm the growing use of multidimensional approaches to resilience assessment, in which physical reliability is considered alongside functionality, recovery time, adaptability, cross-sectoral interdependencies, and changes in the state of the system after a shock. Criticality in the international research discourse is therefore increasingly determined not only by the physical characteristics of an asset but by the function it performs within the wider system.

Ukrainian scholarship initially followed a somewhat different research logic. The development of the national critical infrastructure protection system led to the predominance of security-oriented, regulatory, legal, and public governance approaches. However, following the beginning of the Russo-Ukrainian war, and particularly after the full-scale invasion, the scope of research expanded considerably. O. Sukhodolia [18] examines critical infrastructure resilience through its capacity to maintain vital functions and services, which effectively brings the Ukrainian approach closer to the international functional paradigm of resilience. O. Shpatakova, R. Ivanenko, and M. Pohrebytskyi [19] focus on the specific challenges of restoring critical infrastructure in de-occupied territories, where reconstruction is directly connected with the restoration of territorial integrity, economic activity, and the basic conditions required for everyday life. V. Mykytenko [20], in turn, interprets the post-war recovery of critical infrastructure as part of its reconstructive development, implying a transition towards qualitatively new parameters of system functioning.

The distinction between these two research traditions is therefore gradually diminishing. International research historically shifted earlier from the protection of individual assets towards the preservation of critical functions, whereas the Ukrainian discourse has evolved from a security and institutional interpretation of critical infrastructure towards an integrated understanding that combines protection, functional resilience, recovery, and long-term development. At the same time, the Ukrainian approach understandably retains a stronger emphasis on military conditions, territorial considerations, and public governance.

A second important area of comparison concerns the interpretation of risk. International research generally conceptualises critical infrastructure as a highly interdependent system in which the failure of one node may trigger a chain of secondary disruptions. This perspective shifts the focus of analysis away from immediate physical damage towards the functional and economic consequences generated as disruption propagates through the system. S. Hallegatte, J. Rentschler, and J. Rozenberg [21] demonstrate that the economic significance of infrastructure resilience is determined not only by reducing the value of physical damage but also by shortening service disruptions and limiting the associated welfare losses. S.-A. Mitoulis et al. [2] adapt this logic to conflict environments, where functional interdependencies, cascading effects, and the restoration of critical services become integral elements of a broader conflict-resilience framework.

Ukrainian research on risk has largely developed around the identification of specific military threats and the determination of protection priorities. A representative example is the study by R. Murasov and Ya. Melnyk [22], which applies expert assessment to quantitatively prioritise threats to critical infrastructure under missile and drone attacks. This methodological orientation directly reflects Ukraine's current needs, while also illustrating an important difference between the two research traditions: international scholarship focuses more extensively on the behaviour of interconnected systems after a shock, whereas Ukrainian studies devote considerable attention to identifying and ranking the sources of danger themselves. For the purposes of investment justification for resilient recovery, however, these approaches should not be regarded as mutually exclusive; rather, they are complementary.

The most visible difference remains the degree of quantitative formalisation. Alongside indicator-based systems, international research makes extensive use of probabilistic, network-based, multi-criteria, and dynamic models. H. O. Caetano et al. [3], for example, employ dynamic Bayesian networks to assess critical infrastructure resilience and to model the propagation of evidence across system components. The studies reviewed by M. Sathurshan et al. [16] and B. Rathnayaka et al. [17] assess resilience using indicators of functional performance, recovery time, vulnerability, adaptability, and other parameters. Such approaches make it possible to move beyond recording the current state of infrastructure towards analysing how an infrastructure system may behave under different conditions.

Ukrainian studies more commonly employ systemic, institutional, expert-based, comparative, and structural-logical methods. Their principal advantage lies in their ability to capture national specificities, actual constraints on public governance, and the distinctive characteristics of the wartime environment. At the same time, some studies already demonstrate a movement towards greater formalisation of risk assessment [22]. This creates the basis for the further development of scenario-based and dynamic modelling, in which the object of analysis should extend beyond the level of threat or resilience observed at a particular point in time to include changes in recovery and investment needs over time.

The Build Back Better concept forms a separate methodological dimension. In international approaches, it fundamentally changes the relationship between damage and recovery needs. According to the guidance provided by the Global Facility for Disaster Reduction and Recovery [12] and the study by S. Hallegatte, J. Rentschler, and B. Walsh [13], reconstruction should not reproduce pre-existing vulnerabilities but should use post-crisis recovery as an opportunity to strengthen infrastructure systems, accelerate their recovery, and increase their inclusiveness. From an economic perspective, this means that required investment may exceed the cost of simply replacing a damaged asset because it also incorporates expenditure on modernisation, redundancy, protection, autonomy, and other characteristics that contribute to future resilience.

In Ukrainian research, a similar idea acquires a specific meaning because recovery and development need to be pursued simultaneously. V. Mykytenko [20] directly links the reconstruction of critical infrastructure with improvements in its quality and reliability, while O. Lazor, I. Yunyk, and A. Zabolotnyi [23] consider post-war recovery within the framework of a national strategy that should encompass not only the reconstruction of damaged facilities but also the modernisation of vital sectors and the identification of appropriate financing sources. Thus, the international approach more explicitly formalises the principle of "building back better", whereas the Ukrainian perspective adds the question of whether and how such a transition can be implemented institutionally under conditions of extensive destruction, resource constraints, and an uncertain security environment.

The investment dimension of recovery is also interpreted differently, although the two perspectives are becoming increasingly aligned. In the international discourse [12; 13; 21], investment in resilience is evaluated according to its capacity to reduce future disruptions and losses rather than solely by the volume of capital expenditure. T. Becker et al. [14], when examining the prospects for Ukraine's reconstruction, emphasise the need to combine external financing with institutional reforms, modernisation, and European integration. The OECD [24] additionally highlights the importance of a clear prioritisation framework, the availability of implementation-ready projects, efficient use of resources, and consistency between reconstruction efforts and long-term digitalisation and decarbonisation objectives.

Historical studies of post-war recovery further reinforce this argument. B. Eichengreen [4] demonstrates the importance of institutional coordination, investment, and structural adaptation for Europe's post-war economic growth. R. Mallett and A. Pain [25], in their analysis of post-conflict recovery, draw attention to the role of markets, the private sector, and infrastructure linkages in restoring economic activity. The outcome of reconstruction, therefore, is determined not simply by whether capital has been mobilised, but by how those resources are transformed into a new functional and institutional configuration of the economy.

The Ukrainian context fundamentally complicates this logic because investment decisions have to be made before the principal destructive factor has ceased to operate. A reconstructed facility may be damaged again, while the actual level of need may continue to change even as the investment portfolio is being designed and implemented. The works of Ukrainian researchers [18–20; 22–23] convincingly demonstrate the importance of functional resilience, territorial specificities, military threats, public-sector coordination, and the strategic nature of post-war recovery. At the same time, a particularly important task for the Ukrainian academic discourse is to move beyond assessing what has been damaged and to what extent, towards determining how much should be invested, in what sequence, and towards what target state of the system in order for such investment to be economically justified.

The comparative analysis therefore points not to a fundamental opposition between international and Ukrainian research approaches, but rather to their potential methodological complementarity. A major strength of the international discourse lies in its high degree of formalisation of resilience, its analysis of cross-sectoral interdependencies and cascading effects, and its attention to the dynamics of system functioning. Ukrainian studies, by contrast, provide a deeper reflection of the specific characteristics of the wartime environment, territorial heterogeneity, institutional and resource constraints, and the need to address protection, recovery, and modernisation simultaneously. Combining these research perspectives provides a theoretical and methodological foundation for moving from a static assessment of reconstruction costs towards scenario-based analysis of investment needs and strategic trajectories for the resilient recovery of Ukraine's critical infrastructure.

**Identification of previously unresolved parts of the overall problem.** Despite substantial progress in research on critical infrastructure resilience, risk management, post-war recovery, and the principles of Build Back Better, the investment dimension of this field remains methodologically fragmented. In most existing approaches, the assessment of physical damage, the estimation of recovery needs, the analysis of resilience, and the justification of investment decisions are treated as relatively independent analytical tasks. As a result, the transition from the estimated cost of recovery to the determination of an investment volume and structure capable of ensuring not only asset reconstruction but also the restoration of critical functions, the reduction of future vulnerability, and the achievement of a target level of resilience remains insufficiently formalised.

A separate unresolved issue is the predominantly static interpretation of investment needs. Conventional approaches to damage and needs assessment are useful for establishing a baseline estimate of the scale of reconstruction, but they are considerably more difficult to apply in an environment where the level of need itself changes during the implementation of recovery measures. This is particularly important for Ukraine, where new and repeated destruction, revisions of existing assessments, changes in the cost of works and equipment, different rates of financing utilisation, and limited project readiness may simultaneously increase or reduce residual needs. Investment needs should therefore be viewed not as a one-off estimate, but as a dynamic outcome of the interaction between accumulated damage, newly incurred losses, the pace of project implementation, and the characteristics of the selected recovery model. In the present study, this interdependence is treated as a key property of the object of scenario modelling.

The combined consideration of the external risk environment and the strategic choice concerning the target state of infrastructure also remains insufficiently developed. Existing studies generally examine either the impact of threats on system resilience or the advantages of particular recovery and modernisation models. Yet the same strategy may have very different economic consequences under stabilisation, prolonged military pressure, or the escalation of compound threats. Similarly, at the same level of risk, minimum recovery, functional adaptation, modernisation, and resilient transformation may generate different trajectories of capital requirements and residual vulnerability. It is therefore essential to distinguish analytically between external conditions that are beyond the control of the decision-maker and the strategic trajectory that results from a deliberate management choice. Such a distinction makes it possible to compare alternative strategies under the same level of risk exposure and to avoid conflating external uncertainty with the parameters of the recovery strategy itself.

Another research gap concerns the insufficient distinction between long-term needs, the priority project portfolio, committed financing, investments actually implemented, and the functional outcomes ultimately achieved. A financing gap is only one of the barriers to recovery. Even when financial resources are formally available, incomplete projects, equipment shortages, limited contractor capacity, security constraints, or a mismatch between the selected technical solution and the critical function may create additional project preparation, implementation, physical, functional, and resilience gaps. Consequently, assessing reconstruction performance solely in terms of funds mobilised or spent does not reveal the extent to which systemic vulnerability has actually been reduced. For this reason, investment analysis needs to move beyond the value of a damaged asset towards the broader logic of "investment – function – time – risk – avoided losses."

A comprehensive approach that simultaneously links the dynamics of investment needs, alternative strategic recovery trajectories, changes in the wartime and post-war risk environment, implementation capacity, and the economic effects of increased resilience therefore remains insufficiently developed. Overcoming this methodological fragmentation requires a scenario-based formulation of the problem in which investment needs are assessed not in isolation, but as the outcome of the interaction between external risks and managerial choices concerning the future configuration of critical infrastructure.

**Formulation of the article's objectives.** The aim of the study is to develop and test a scenario-based approach to assessing investment needs and substantiating strategic trajectories for the resilient recovery of Ukraine's critical infrastructure, taking into account the dynamics of their formation, implementation capacity, financial constraints, and the changing wartime and post-war risk environment.

Achieving this aim requires addressing the following tasks: to systematise the dynamics of direct damage, economic losses, and recovery needs based on the results of RDNA1–RDNA5 and determine the role of the infrastructure component within their overall structure; to distinguish between direct damage, estimated recovery needs, the required volume of investment, committed financing, investments actually implemented, and the functional outcomes achieved; to develop a system of strategic trajectories reflecting alternative target states of critical infrastructure, ranging from minimum restoration of damaged assets to the resilient transformation of the system; to identify types of external risk environments and integrate them with strategic alternatives into a single scenario matrix; to conduct simulation-based assessment of the dynamics of residual investment needs for 2026–2030 under different combinations of scenario parameters; to determine how the pace of investment implementation, additional expenditure on resilience enhancement, and reductions in future risk affect the long-term dynamics of required resources; and to substantiate criteria for selecting a strategic trajectory on the basis of the relationship between "investment – function – time – risk – avoided losses".

The methodological foundation of the study comprises systemic, functional, risk-oriented, resilience-based, and scenario-based approaches. The research employs methods of analysis, synthesis, and scientific generalisation; comparative and structural-logical analysis; systematisation and dynamic analysis of RDNA1–RDNA5 data; scenario and simulation modelling; and multi-criteria assessment to substantiate the selection of strategic trajectories for the resilient recovery of critical infrastructure.

Within this study, scenario modelling is not regarded as a tool for producing a deterministic forecast of reconstruction costs, but rather as a means of comparing alternative management decisions under different combinations of external risks and recovery parameters. This approach makes it possible to assess not only the scale of the resources required but also the long-term consequences of choosing among minimum-restoration, functional-adaptive, modernisation, and resilience-transformation trajectories for the recovery of critical infrastructure.

**Presentation of the main research material.** Scenario-based assessment of critical infrastructure investment needs should not be structured around the search for a single final "cost of reconstruction", but rather around a sequence of decisions that transform assessed damage into a restored critical function. This approach is particularly important for Ukraine, where reconstruction is taking place under conditions of a continuing military threat, repeated damage, restricted access to certain territories, changing price conditions, and uneven capacity to implement projects. The PDNA and Disaster Recovery Framework methodologies provide the basic framework for distinguishing between damage, losses, needs, and priorities, while the Build Back Better approach adds the requirement not to reproduce pre-existing vulnerabilities, but to reduce future risk [5–6; 12–13].

For investment analysis, it is essential to distinguish between five categories: direct damage, estimated recovery needs, the required volume of investment taking into account the target state of the infrastructure, investments actually implemented, and the functional outcome achieved. Treating these categories as equivalent distorts management decisions: the availability of financing does not yet mean that implementation has taken place, the completion of construction works does not guarantee the restoration of the service, and the physical reconstruction of an asset does not necessarily reduce systemic risk. In a concise form, this relationship can be expressed as:

$$D_{i,t} \not\equiv N_{i,t} \not\equiv I_{i,t}^{req} \not\equiv I_{i,t}^{impl} \not\equiv R_{i,t}^{func}, \quad (1)$$

where $D_{i,t}$ denotes the direct damage to asset or system $i$ in period $t$; $N_{i,t}$ denotes estimated recovery needs; $I_{re}q_{i,t}$ denotes the required investment taking into account the target state of the infrastructure; $I^{impl}{}_{i,t}$ denotes investment actually implemented; $R^{func}{}_{i,t}$ denotes the achieved level of functional recovery. Equation (1) is conceptual in nature: it represents different stages of a single process rather than an arithmetic inequality between indicators.

The empirical basis of the calculations consists of five consecutive Rapid Damage and Needs Assessments – RDNA1–RDNA5 [7–11]. They are used as a system of interconnected analytical snapshots rather than as a homogeneous statistical time series. The assessments were prepared as of different dates, cover different durations of the war, and incorporate revisions to sectoral boundaries, price assumptions, and needs that had already been met. RDNA5 is therefore used as the baseline for the scenario simulation, while the preceding assessments are employed to identify structural changes, verify the direction of observed dynamics, and establish sensitivity ranges.

The consecutive assessments demonstrate not only an expansion in the scale of destruction, but also a substantial change in the relationship between physical damage and the economic consequences of disrupted functions. Between RDNA1 and RDNA5, direct damage increased from USD 97.4 billion to USD 195.1 billion, approximately doubling, whereas economic losses rose from USD 252.0 billion to USD

666.7 billion, an increase of 164.6%. Ten-year recovery needs increased from USD 348.5 billion to USD 587.7 billion (Table 1) [7–11].

Table 1 – Dynamics of the Overall RDNA1–RDNA5 Estimates

| Indicator | RDNA1 | RDNA2 | RDNA3 | RDNA4 | RDNA5 | Change, RDNA1–RDNA5, % |
|---|---|---|---|---|---|---|
| Direct damage, USD billion | 97.4 | 134.7 | 152.5 | 176.1 | 195.1 | 100.3 |
| Economic losses, USD billion | 252.0 | 289.1 | 499.3 | 588.8 | 666.7 | 164.6 |
| Recovery needs, USD billion | 348.5 | 410.6 | 486.2 | 523.6 | 587.7 | 68.6 |
| Losses / damage, times | 2.59 | 2.15 | 3.27 | 3.34 | 3.42 | 32.0 |
| Recovery needs / damage, times | 3.58 | 3.05 | 3.19 | 2.97 | 3.01 | -15.9 |

*Note*: Relative changes were calculated using the values reported in the respective assessments; minor discrepancies may occur due to rounding.

*Source*: systematised and calculated by the author based on [7–11].

The most important finding is that economic losses have increased faster than direct damage. The rise in the losses-to-damage ratio to 3.42 indicates that the economic cost of the war accumulates not only through the destruction of assets, but also through prolonged disruptions, additional operating costs, foregone revenues, and services that could not be provided. At the same time, the relative stability of the recovery-needs-to-damage ratio at around three after RDNA2 does not justify the use of a universal coefficient for converting damage into recovery needs. The aggregate ratio conceals substantial sectoral differences and depends on the selected recovery standard, the structure of prices, and methodological revisions.

For the purposes of this article, energy and extractive industries, transport, telecommunications and digital infrastructure, water supply and sanitation, and municipal services are combined into an analytical "RDNA infrastructure block" (Table 2). This grouping is used solely to ensure comparability across the five assessments and should not be equated with the legally defined list of critical infrastructure sectors. When moving from aggregate assessment to individual projects, priority should instead be determined by the criticality of the function, the number and scope of affected users, substitutability, cross-sectoral interdependencies, and cascading potential.

Table 2 – Dynamics of the RDNA Infrastructure Block across RDNA1–RDNA5

| Indicator | RDNA1 | RDNA2 | RDNA3 | RDNA4 | RDNA5 |
|---|---|---|---|---|---|
| Damage to the infrastructure block, USD billion | 37.3 | 52.5 | 55.2 | 66.9 | 78.5 |
| Share of total damage, % | 38.3 | 39.0 | 36.2 | 38.0 | 40.2 |
| Losses of the infrastructure block, USD billion | 49.8 | 70.9 | 115.4 | 140.9 | 172.2 |
| Share of total losses, % | 19.8 | 24.5 | 23.1 | 23.9 | 25.8 |
| Recovery needs of the infrastructure block, USD billion | 98.9 | 156.4 | 148.0 | 169.4 | 218.9 |
| Share of total recovery needs, % | 28.4 | 38.1 | 30.4 | 32.4 | 37.2 |
| Energy sector recovery needs, USD billion | 10.4 | 47.0 | 47.1 | 67.8 | 90.6 |

*Source*: systematised and calculated by the author based on [7–11].

The recovery needs of the infrastructure block increased by USD 120.0 billion and accounted for approximately half of the overall increase in recovery needs between RDNA1 and RDNA5. The most recent interval between assessments is particularly illustrative: out of the USD 64.1 billion increase in total recovery needs, approximately USD 49.5 billion, or 77.2%, was attributable to the infrastructure block. This indicates that the infrastructure component is becoming increasingly important not only as a consequence of physical destruction, but also as a source of prolonged functional losses.

Moving from aggregate recovery needs to an investment decision requires decomposition according to economic content. Within the proposed framework, basic physical restoration is separated from the costs of restoring service delivery, preparatory works, technological modernisation, and the resilience premium. Such a hierarchy reduces the risk of double counting while also making it possible to compare alternative target states of the system.

$$N_{r,s,t}^{(k)} = N_{r,s,t}^{base,(k)} + N_{r,s,t}^{serv,(k)} + N_{r,s,t}^{enable,(k)} + \Delta N_{r,s,t}^{mod,(k)} + \Delta N_{r,s,t}^{res,(k)}, \quad (2)$$

where $r$ denotes the territory; $s$ denotes the sector or critical function; $t$ denotes the period; $k$ denotes the scenario; $N^{base}$ denotes basic physical restoration or replacement; $N^{serv}$ denotes the costs of restoring service delivery and operational capacity; $N^{enable}$ denotes demining, access provision, dismantling, design, and other preparatory activities; $\Delta N^{mod}$ denotes the additional cost of a modern technological equivalent; $\Delta N^{res}$ denotes expenditure on protection, redundancy, autonomy, decentralisation, cyber resilience, and the reduction of systemic risk.

A key property of the model is the dynamic nature of residual recovery needs. Even when investments are being implemented, residual needs may increase if new and repeated damage, reassessment effects, price changes, and higher recovery standards exceed the volume of completed works. This fundamentally distinguishes wartime recovery from one-off post-crisis reconstruction:

$$N_{i,t+1}^{resid} = N_{i,t}^{resid} + N_{i,t+1}^{new} + N_{i,t+1}^{repeat} + N_{i,t+1}^{reval} + N_{i,t+1}^{price} + N_{i,t+1}^{standard} + \Delta N_{i,t+1}^{res} - I_{i,t}^{impl} \quad (3)$$

Equation (3) shows that changes in residual needs result from two opposing flows. Residual needs increase as a result of new and repeated damage, reassessment, rising costs, new standards, and the resilience component, while they decrease through works actually implemented. Consequently, an increase in residual recovery needs does not in itself indicate an absence of reconstruction, just as a decline in residual needs does not necessarily demonstrate the full restoration of a critical function.

A second constraint is implementation capacity. Committed financial resources can be utilised only when there is an adequately prepared project portfolio, access to the facility, available equipment, contractors, and effective management coordination. The maximum volume of actual implementation is expressed as:

$$I_{i,t}^{impl} = \min\{I_{i,t}^{req}, CF_{i,t}, V_{i,t}^{ready}, C_{i,t}^{delivery}\} \cdot \varphi_{i,t}, \qquad 0 \le \varphi_{i,t} \le 1, \quad (4)$$

where $CF_{i,t}$ denotes committed financing; $V^{ready}_{i,t}$ denotes the value of the implementation-ready project portfolio; $C^{delivery}_{i,t}$ denotes the physical and institutional delivery capacity; $\varphi_{i,t}$ denotes a coefficient reflecting the impact of security, procurement, logistics, and coordination constraints. The use of the minimum operator prevents the model from assuming that resources can be utilised beyond any of the actual implementation limits.

The strategic trajectory determines not the pace at which funds are spent, but the target state that the recovery process is intended to achieve. The study identifies four alternatives (Table 3), forming a progression from the short-term restoration of basic operability to the transformation of the system configuration in order to reduce future risk. These alternatives should not be interpreted as interchangeable "better" or "worse" scenarios. The rationality of each depends on the criticality of the function, the decision horizon, the security environment, and implementation capacity

Table 3 – Comparative Characteristics of Strategic Trajectories for Resilient Recovery

| Characteristic | Minimum-Restoration | Functional-Adaptive | BBB Modernisation | Resilience-Transformation |
|---|---|---|---|---|
| Objective | Rapid restoration of basic operability | Restoration of the critical function and reduction of downtime | Modern technological equivalent | New system configuration with lower systemic risk |
| Object of investment | Damaged asset | Function, reserve capacities, and temporary solutions | Asset + technological modernisation | System, network, interdependencies, and life cycle |
| Priority | Minimum CapEx, rapid repair | Critical loads, recovery time, substitutability | Efficiency, digitalisation, EU standards | Protection, decentralisation, redundancy, autonomy |
| Spatial logic | Predominantly the previous location | Selective relocation or mobile solutions | Reconsideration of location based on future demand | Dispersion of critical nodes and elimination of single points of failure |
| Financial logic | Emergency and budget financing | Blended financing for critical projects | International financial institutions, programme funding, private capital | Portfolio financing, guarantees, insurance, public-private partnerships |
| Expected outcome | Asset restored, with part of the previous vulnerability retained | More resilient operational function | Higher performance and compliance with standards | Lower future losses and greater system adaptability |
| Time horizon | Short term; emergency phase | Short- and medium-term; phased recovery | Medium- and long-term | Long-term; multi-phase transformation |
| Key performance criterion | Time required to restore basic operability | Share of the critical function restored and reduction in TTR | Life-cycle costs, efficiency, and technological outcomes | Reduction in expected losses, cascading risk, and residual vulnerability |
| Main risk of inappropriate application | Preservation of pre-existing vulnerability and repeated financing | Temporary solutions becoming permanent and fragmentation of the system | Technological overcomplication, delayed commissioning, and mismatch with future demand | Excessive capital intensity, coordination complexity, and system design errors |

*Source*: developed by the author based on [5–14; 21; 24; 26; 27–29].

The proposed strategic trajectories should be interpreted not as four mutually exclusive stages of a single process, but as ideal-type investment regimes that define different target states of the system and different logics for allocating scarce resources. At the national or sectoral portfolio level, they may be applied simultaneously, while for an individual facility they may replace one another sequentially. For example, the emergency restoration of a service may initially be achieved through a minimum-restoration or functional-adaptive solution, whereas capital modernisation or transformation may be undertaken after security and project conditions have stabilised. This approach reduces the risk of artificially selecting a single universal scenario for different sectors and territories [5; 12–13; 26].

Minimum-restoration trajectory. Its economic logic is based on minimising the time required to restore basic operability and the initial CapEx. It is rational for localised damage, emergency works, facilities with limited cascading potential, or as a temporary bridge towards a more sophisticated solution. At the same time, restoring a particular asset should not become an end in itself. If the critical function can be provided more effectively through another technological solution, relocated to another site, or integrated into a different network, the managed non-restoration of an obsolete asset may be economically more justified than mechanically reproducing the pre-war configuration [14; 24].

The principal risk associated with this trajectory arises from path dependence. Rapid repair of a centralised node, insufficient redundancy, or the repeated use of unique equipment may preserve previous vulnerabilities and create technological lock-in. Where the probability of repeated damage is high, a cheaper initial solution may generate higher expected costs of future repairs and service interruptions. The minimum-restoration regime should therefore be concluded not only with the commissioning of the facility, but also with an explicit assessment of residual risk and the conditions under which a transition to an adaptive, modernisation, or transformation model becomes necessary [5; 7–11; 21].

Functional-adaptive trajectory. Unlike the first model, its primary object is the critical service rather than a particular asset. The investment portfolio is formed from permanent, reserve, mobile, and organisational solutions that make it possible to reduce the functional deficit even before capital reconstruction has been completed. In the energy sector, such solutions may include mobile substations, distributed generation, or microgrids; in water supply, reserve sources and modular systems; and in digital infrastructure, duplicated communication channels, autonomous power supply, and backup data centres. Under conditions of prolonged wartime risk, this trajectory effectively allows investment not merely in physically restored assets, but in time and continuity of critical functions [5; 18; 21].

Its weakness lies in the risk that temporary solutions may become permanent. The accumulation of incompatible equipment, differing donor standards, and local bypass arrangements may reduce the future manageability of the system and increase operating costs. The functional-adaptive model therefore requires a predefined exit trajectory, including interoperability standards, rules for integrating temporary assets into the target architecture, and triggers for transition to modernisation. The key indicators in this case are the share of critical load restored, TTR, the availability of reserve capacity, and the duration of service interruptions, rather than the number of repaired facilities [20; 21].

Build Back Better modernisation trajectory. This model assumes that reconstruction should create a modern technological equivalent rather than a replica of the damaged asset. The investment decision incorporates life-cycle costs, energy and resource efficiency, digitalisation of management, maintainability, compatibility with European Union standards, and alignment with the expected structure of future demand. Its application is most justified where the future function is expected to remain consistently necessary, the project has a sufficiently long operating horizon, and the operator has the capacity to maintain a technologically more complex solution [12–14; 24; 26].

At the same time, Build Back Better should not be equated with maximising technical complexity. Overdesign, a prolonged project cycle, or dependence on uncertain future demand may increase the losses associated with delayed commissioning. Moreover, new equipment does not in itself eliminate systemic vulnerability: a highly efficient but excessively centralised node without adequate redundancy may remain a single point of failure. The modernisation trajectory is therefore economically justified when the life-cycle and technological benefits exceed the cost of delayed commissioning and when the project simultaneously meets minimum thresholds for security, autonomy, and maintainability [5; 12–13].

Resilience-transformation trajectory. Its defining feature is that it changes not an individual asset, but the configuration of the infrastructure system itself. It is most justified for functions characterised by high criticality, low substitutability, substantial cross-sectoral interdependencies, and a high probability of repeated or compound impacts. Investment is directed towards alternative routes, the spatial dispersion of critical nodes, consumer autonomy, physical and cyber protection, decentralised capacity, and rapid reconnection mechanisms. In this case, the resilience premium cannot be defined as a single percentage of the value of damage. Its economic meaning depends on the extent to which additional investment reduces expected future losses and shortens the duration of functional deficits [12–13; 21; 26].

The transformation model places the greatest demands on data, project preparation, and coordination, because a system design error may be more costly than a local repair error. At the same time, it does not necessarily imply restoring a larger number of assets. Some obsolete or excessively vulnerable nodes may be replaced by alternative technologies, relocated, or excluded from the future system configuration. The performance of this trajectory should therefore be assessed not by the amount of CapEx utilised, but by the reduction in residual systemic risk, shorter TTR, the magnitude of avoided losses, and a reduction in cascading potential [5; 14; 21; 26].

In practice, the choice of trajectory should be regarded as conditional rather than prescriptive. As the criticality of a function, the recurrence of threats, and cascading potential increase, and as substitutability declines, the case for functional-adaptive and resilience-transformation solutions becomes stronger. Conversely, high urgency combined with low project readiness increases the role of minimum-restoration and adaptive measures. In a stabilisation and post-war environment, when the inflow of new damage declines and the planning horizon becomes longer, part of the portfolio will naturally shift towards modernisation and systemic transformation. The strategic trajectory is therefore a controllable variable of investment policy rather than a direct function of the fact of destruction itself.

For a methodologically sound scenario analysis, the strategic choice must be separated from the external environment. A scenario is defined as a combination of a strategic trajectory and a risk environment:

$$S_k = T_q \times E_p, \tag{5}$$

where $Tq$ denotes the strategic trajectory and $Ep$ denotes the external risk environment. This two-dimensional framework separates the controllable strategic choice from conditions that arise beyond the boundaries of a specific project.

Table 4 – Characteristics of External Risk Environments

| Risk Environment | Security Characteristics | Macroeconomic and Financial Conditions | Data and Access | Implications for the Model |
|---|---|---|---|---|
| Stabilisation and post-war transition | Substantial decline in the intensity of attacks; persistence of localised, mine-related, cyber, and technological risks | More predictable funding flows, but persistently high demand for capital and reconstruction resources | Improved access and verification; territorial and demographic uncertainties remain | Lower inflow of new damage; greater scope for longer-term integrated projects; increasing share of modernisation |
| Prolonged wartime risks | Regular attacks on particular sectors and territories | Limited availability of long-term capital; high dependence on international support | Uneven access; periodic revision of data | Phased implementation, mobile solutions, redundancy, and priority given to rapid restoration of critical functions |
| Escalation and compound threats | Intensive repeated attacks; cyber and cascading impacts | Higher risk premium, more expensive resources, and tight fiscal constraints | Significant areas of uncertainty and restricted access | Increase in new and repeated damage; higher protection costs; preference for autonomous and spatially dispersed solutions |

*Source*: developed by the author taking into account [7–11; 14; 24].

Table 5 – "Strategic Trajectory – Risk Environment" Matrix

| Strategic Trajectory | Stabilisation / Post-War Transition | Prolonged Wartime Risks | Escalation and Compound Threats |
|---|---|---|---|
| Minimum-restoration | Selective repair only where modernisation is economically unjustified or the function has low criticality | Rapid emergency repairs with a high risk of repeated financing | Limited to the urgent restoration of local vital functions |
| Functional-adaptive | Transitional model leading to subsequent modernisation; reserve capacities serve as a contingency layer | Core approach based on mobility, redundancy, phased implementation, and rapid restoration of functions | Autonomous and mobile solutions for critical loads become predominant |
| BBB modernisation | Principal mode of technological renewal and alignment with European Union standards | Phased modernisation of the most implementation-ready and adequately protected projects | Applied selectively to facilities where a longer implementation cycle does not create an unacceptable service deficit |
| Resilience-transformation | System-level redesign of networks, elimination of critical dependencies and single points of failure | Selective transformation of nodes with high cascading potential | Highest relevance for critical systems, but also the most demanding in terms of protection, financing, and coordination |

*Source*: proposed and developed by the author based on the analysis of reports by international organisations and analytical centres and the findings of previous studies [27–29].

The risk environment (Table 4) determines the intensity of new and repeated damage, the risk premium, access to capital, and the level of informational uncertainty, whereas the strategic trajectory determines the target state, the additional modernisation or resilience component, the pace of actual implementation, and the mechanism through which future risk is reduced.

The matrix should therefore not be interpreted as a set of twelve independent forecasts, but rather as a stress-testing architecture (Table 5). It makes it possible to compare alternative management decisions under the same level of external pressure and to test the robustness of a particular strategy as the external environment changes.

For the purpose of testing the proposed scenario framework, the recovery needs of the RDNA5 infrastructure block, amounting to USD 218.9 billion as of 31 December 2025, were used as the baseline [11]. The numerical simulation is conducted under a single assumed baseline level of external pressure approximating a prolonged wartime risk environment. This assumption deliberately holds the external component constant in order to isolate the effect of strategic choice itself. The full matrix is subsequently used as a framework for stress-testing the parameters under stabilisation or escalation conditions. The calculation is methodological in nature and should not be interpreted as a statistical forecast or an official estimate of financing requirements. Its purpose is to demonstrate the direction of change in residual needs under different combinations of the rate of new damage, additional expenditure on modernisation and resilience, the effect of future risk reduction, and the actual capacity to implement investment projects.

The simplified equation describing the simulation dynamics is expressed as:

$$N_{t+1}^{(s)} = N_t^{(s)}(1 + g_r - \alpha_s + \pi_{s,t} - m_s), \tag{6}$$

where $N^s_t$ denotes the residual need under trajectory $s$ at the beginning of year $t$; $g^r$ denotes the exogenous rate of increase resulting from new damage, reassessment, and price changes; $\alpha_s$ denotes the effect of reducing future risk; $\pi_{s,t}$ denotes the additional modernisation or resilience component; $m_s$ denotes the share of the initial recovery need that can actually be implemented during the year. For the methodological simulation, $g^r$ is assumed to be 8% for all trajectories, while the remaining parameters are differentiated according to the substantive characteristics of the respective strategies (Tables 6, 7).

Table 6 – Simulation Parameters under the Baseline Risk Environment

| Parameter | Minimum-Restoration | Functional-Adaptive | BBB Modernisation | Resilience-Transformation |
|---|---|---|---|---|
| Exogenous growth in needs $g^r$, % | 8 | 8 | 8 | 8 |
| Future risk reduction effect $\alpha_s$, percentage points | 0 | 2 | 4 | 6 |
| Additional component $\pi_{s,t}$ in 2026–2027, % | 0 | 2 | 4 | 8 |
| Additional component $\pi_{s,t}$ in 2028, % | 0 | 2 | 4 | 4 |
| Additional component $\pi_{s,t}$ in 2029–2030, % | 0 | 2 | 2 | 2 |
| Share of actual implementation $m_s$, % | 5 | 10 | 12 | 15 |
| Net rate in 2026–2027, % | +3 | -2 | -4 | -5 |
| Net rate in 2028, % | +3 | -2 | -4 | -9 |
| Net rate in 2029–2030, % | +3 | -2 | -6 | -11 |

*Note*: The parameters represent scenario assumptions used for methodological testing and should be subject to sensitivity analysis.

*Source*: author's assumptions based on the dynamics of RDNA1–RDNA5 [7–11].

Table 7 – Simulated Dynamics of Residual Recovery Needs of the Infrastructure Block, USD Billion

| Trajectory | 2025, baseline | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|
| Minimum-Restoration | 218.9 | 225.5 | 232.2 | 239.2 | 246.4 | 253.8 |
| Functional-Adaptive | 218.9 | 214.5 | 210.2 | 206.0 | 201.9 | 197.9 |
| BBB Modernisation | 218.9 | 210.1 | 201.7 | 193.7 | 182.0 | 171.1 |
| Resilience-Transformation | 218.9 | 208.0 | 197.6 | 179.8 | 160.0 | 142.4 |

*Source*: calculated by the author using Equation (6).

The results presented in Table 8 reveal fundamentally different patterns of long-term dynamics. The minimum-restoration option does not offset the inflow of new damage and reassessment effects: under the specified parameters, residual needs increase to USD 253.8 billion by 2030. The functional-adaptive trajectory shifts the system towards a moderate reduction in residual needs, bringing them down to USD 197.9 billion. Despite a higher additional component in the initial years, the BBB modernisation trajectory reduces residual needs to USD 171.1 billion, while the resilience-transformation trajectory lowers them further to USD 142.4 billion.

Table 8 – Summary Results of the Simulation for 2026–2030

| Trajectory | Estimated Investment Implemented over 5 Years, USD Billion | Residual Needs in 2030, USD Billion | Change from the 2025 Baseline, % | Dominant Outcome |
|---|---|---|---|---|
| Minimum-Restoration | 58.1 | 253.8 | +15.9 | Substantial volume of repairs without reversing the accumulation of residual needs |
| Functional-Adaptive | 105.2 | 197.9 | -9.6 | Stabilisation of residual needs and faster restoration of critical functions |
| BBB Modernisation | 120.8 | 171.1 | -21.8 | Technological upgrading and sustained reduction in residual needs |
| Resilience-Transformation | 144.6 | 142.4 | -34.9 | System-wide reduction in vulnerability and cascading risk |

*Note*: The amounts of investment implemented are elements of the scenario simulation rather than a budget forecast.

*Source*: calculated by the author.

This result does not imply that the most expensive trajectory is automatically preferable for every facility. Rather, it demonstrates a nonlinear trade-off: higher initial expenditure on protection, redundancy, and system reconfiguration may reduce the future accumulation of needs and shorten the duration of functional disruptions. A comparison based solely on current CapEx therefore systematically undervalues alternatives whose economic benefits emerge over the infrastructure life cycle.

For the practical selection of a scenario, the residual level of investment needs alone is insufficient. It is advisable to consider simultaneously the volume of investment, the functional outcome achieved, the recovery time, the increase in resilience, and the present value of avoided losses. A composite criterion may be expressed as:

$$Score_s = w_1(1 - \tilde{I}_s) + w_2\tilde{R}_s^{func} + w_3\left(1 - \widetilde{TTR}_s\right) + w_4\widetilde{RG}_s + w_5\widetilde{AL}_s, \quad (7)$$

where the normalised indicators represent, respectively, the investment burden, the degree of functional restoration, the time required to restore the function, the increase in resilience, and avoided future losses; $w_j$ denotes the weight assigned to criterion jj, with the sum of all weights equal to one. The weights should be determined on a sector-specific basis: for energy, water supply, or emergency medical infrastructure, greater importance should be assigned to speed and continuity of service, whereas for long-term transport projects, life-cycle costs, capacity, and network effects should carry greater weight.

Scenario-based assessment of investment needs should also be linked to the actual capacity to transform long-term needs into an annual project portfolio (Table 9). The RDNA2–RDNA5 data reveal a substantial gap between ten-year recovery estimates and the scale of annual priorities. During 2023–2026, annual priorities accounted for only 2.59–3.43% of long-term recovery needs, while committed financing in 2024–2026 covered less than half of the identified annual priorities [8–11].

Table 9 – Long-Term Recovery Needs, Annual Priorities, and Financial Provision

| Indicator | RDNA2 / 2023 | RDNA3 / 2024 | RDNA4 / 2025 | RDNA5 / 2026 |
|---|---|---|---|---|
| Long-term recovery needs, USD billion | 410.6 | 486.2 | 523.6 | 587.7 |
| Annual priorities, USD billion | 14.1 | 15.3 | 17.32 | 15.245 |
| Annual priorities / long-term recovery needs, % | 3.43 | 3.15 | 3.31 | 2.59 |
| Committed financing, USD billion | n/a | approximately 5.5 | 7.37 | 5.765 |
| Financing gap, USD billion | n/a | approximately 9.5 | 9.96 | 9.48 |
| Coverage of annual priorities, % | n/a | approximately 35.9 | 42.6 | 37.8 |

*Note*: Due to rounding and differences in financing categories, the sum of committed resources and the financing gap may not exactly equal the annual priority.

*Source*: systematised and calculated by the author based on [8–11].

The financing gap is defined as the difference between the annual priority need and committed financing:

$$FG_t = N_t^{priority} - CF_t. \quad (8)$$

However, this indicator captures only one component of the overall shortfall. Even full financial coverage does not eliminate shortages of implementation-ready projects, equipment, contractor capacity, permits, secure access, and operational capability. Portfolio formation should therefore distinguish at least between financial, project preparation, implementation, technical, functional, and resilience gaps.

Project prioritisation cannot be based solely on the value of the damaged asset or the extent of its physical destruction. To compare alternatives, a multi-criteria index is proposed (Table 10), combining function criticality, functional deficit, population coverage, cross-sectoral interdependencies, substitutability, recovery time, resilience gains, avoided losses, project readiness, financial feasibility, and implementation capacity:

$$PRI_i = \sum_{j=1}^{m} w_j z_{ij}, \qquad \sum_{j=1}^{m} w_j = 1, \qquad w_j \geq 0, \qquad (9)$$

where $z_{ij}$ denotes the normalised value of criterion $j$ for project $i$, and $w_j$ denotes the weight assigned to that criterion. For indicators where a lower value is preferable, such as recovery time or substitutability when interpreted in terms of high irreplaceability, inverse normalisation is applied. The weights should be transparent, tested for sensitivity, and, where possible, determined separately for different sectoral groups.

Table 10 – Criteria for Prioritising Critical Infrastructure Investment Projects

| Criterion | Economic Rationale | Preferred Direction | Example Indicator |
|---|---|---|---|
| Criticality | Importance of the function for vital societal needs and security | Maximum | Composite criticality index |
| Functional deficit | Scale of the service that is unavailable or provided at a reduced level | Maximum | Share of lost capacity, % |
| Coverage | Population and organisations dependent on the function | Maximum | Number of users |
| Cross-sectoral impact | Number and strength of dependent functions | Maximum | Interdependency / cascading potential index |
| Substitutability | Possibility of providing the service through alternative means | Minimum | Switching time and share of demand that can be redirected |
| Recovery time | Time required to restore the target function | Minimum | Days / months |
| Resilience gain | Reduction in vulnerability after project implementation | Maximum | Change in expected risk |
| Avoided losses | Expected economic benefit | Maximum | Discounted value of avoided losses |
| Project readiness | Availability of documentation, permits, and procurement readiness | Maximum | Readiness stage, % |
| Financial feasibility | Realism of financing sources and cost of capital | Maximum | Share of committed financing |
| Implementation capacity | Ability to implement and subsequently operate the project | Maximum | Capacity coefficient |

*Source*: proposed by the author based on the analysis of [5; 7–11; 18; 22; 26; 27–29].

A unified scenario logic does not imply the use of identical parameters across all sectors. Energy, transport, digital infrastructure, water supply, and municipal systems differ in the duration of project cycles, the nature of network interdependencies, the potential for private financing, and the consequences of functional deficits. For this reason, applying a universal resilience premium or assuming the same implementation rate across sectors would be methodologically unjustified.

In the energy sector, priority is determined by available capacity, critical loads, redundancy, and the effects on dependent systems; in transport, by route capacity, the availability of alternatives, and network bottlenecks; in digital infrastructure, by network availability, power autonomy, channel redundancy, and cyber resilience; in water supply, by the ability to localise failures, the availability of reserve sources, and dependence on energy supply; while for municipal infrastructure, territorial differentiation, migration-related changes, and the capacity of local communities become particularly important. The value of a damaged asset should therefore be supplemented by functional and systemic criteria.

A separate limitation concerns the RDNA data. The five assessments do not constitute a regular statistical time series, and their values reflect not only new physical damage but also reassessment effects, price and exchange-rate changes, revisions to classifications, and partial accounting for completed recovery works [7–11]. The simulation for 2026–2030 should therefore be interpreted as a scenario experiment rather than a forecast. A transition to autoregressive or other forms of statistical forecasting would require the construction of a harmonised quarterly or monthly time series in constant prices, consistent sectoral boundaries, a clear distinction between gross and residual needs, and the inclusion of explanatory variables capturing new damage, financing, implementation, risk, and price dynamics.

Taking these limitations into account, the proposed approach should be regarded as a tool for economic and portfolio-level decision-making prior to detailed engineering design. Its practical value lies in the possibility of comparing alternatives within a common analytical framework without reducing reconstruction performance to the amount of funds disbursed. The decisive criterion becomes the relationship between "investment – function – time – risk – avoided losses." A trajectory can be considered justified when, given the criticality of the function, the acceptable duration of service disruption, and actual resource constraints, it provides the best balance between the speed of service restoration and the reduction in the expected cost of future disruptions.

**Conclusions.**

The study has shown that investment needs for the recovery of Ukraine's critical infrastructure cannot be treated as a fixed value derived directly from the monetary scale of physical destruction. Under conditions of an ongoing war, these needs evolve dynamically under the influence of accumulated, new, and repeated damage; economic losses resulting from disruptions to critical functions; changes in the cost of works and equipment; the selected recovery standard; the availability of financing; project readiness; and the actual capacity to implement investment projects. Economically justified assessment should therefore be based not only on the value of the damaged asset, but also on the functional condition that the infrastructure system needs to achieve and the level of future risk that can be considered acceptable.

The analysis of RDNA1–RDNA5 confirmed that economic losses have accumulated faster than direct damage. Between the first and fifth assessments, direct damage increased by 100.3%, economic losses by 164.6%, and ten-year recovery needs by 68.6%. Under RDNA5, the needs of the infrastructure block constructed for the purposes of this study reached USD 218.9 billion, accounting for 37.2% of total estimated recovery needs. This indicates that the economic consequences of infrastructure destruction are determined not only by the physical loss of assets, but also by the duration of service disruptions, the scale of functional deficits, and the cascading transmission of adverse effects across interdependent sectors.

The proposed scenario framework is based on four strategic trajectories: minimum-restoration, functional-adaptive, Build Back Better modernisation, and resilience-transformation. These trajectories differ primarily in the target condition of the infrastructure, ranging from the rapid restoration of basic operability to a deeper transformation of the system configuration aimed at reducing future losses and systemic vulnerability. Importantly, these trajectories are not treated as a universal sequence or a rigid hierarchy. The rationality of each depends on the criticality of the function, time constraints, available resources, the level of threats, substitutability, and cascading potential.

One of the key results of the study is the development of a two-dimensional scenario architecture based on the relationship "strategic trajectory – risk environment." The matrix combines four management alternatives with three types of external conditions: a stabilisation and post-war transition environment, a prolonged wartime risk environment, and an environment characterised by the escalation of compound threats. This distinction makes it possible to separate controllable recovery parameters from exogenous conditions and, consequently, to compare alternatives more accurately under the same level of external pressure or to assess the robustness of a particular trajectory under different scenarios for the evolution of the security environment.

The simulation exercise based on the RDNA5 needs of the infrastructure block demonstrated substantially different dynamics of residual investment needs. Under the adopted scenario assumptions, the minimum-restoration trajectory does not offset the inflow of new damage and reassessment effects, causing residual needs to increase to USD 253.8 billion by 2030. Under the functional-adaptive trajectory, residual needs decline to USD 197.9 billion; under the modernisation trajectory, to USD 171.1 billion; and under the resilience-transformation trajectory, to USD 142.4 billion. These values should not be interpreted as forecasts of future budget expenditure or financing. Their analytical significance lies elsewhere: higher initial expenditure may be economically justified if it slows the accumulation of new needs, shortens the duration of functional disruptions, and reduces expected losses over the infrastructure life cycle.

A further result concerns the distinction between long-term needs, annual priorities, committed financing, realised investment, and the actual functional outcome achieved. During 2023–2026, annual priorities represented only about 2.6–3.4% of long-term needs, while in 2024–2026 committed financing covered less than half of the identified priorities. At the same time, insufficient capital is not the only limiting factor. Between estimated needs and the level of functionality ultimately achieved, financial, project preparation, implementation, technical, functional, and resilience gaps may emerge successively. The amount of financing mobilised or actually utilised therefore cannot be treated as a self-sufficient indicator of reconstruction performance.

The scientific novelty of the results lies in the further development of a scenario-based approach to assessing critical infrastructure investment needs through the integration of several analytical components: distinguishing the strategic trajectory as the outcome of a management decision from the risk environment as an exogenous condition; constructing a matrix of twelve scenario combinations; representing residual investment needs as a dynamic variable that changes under the influence of new and repeated damage, realised investment, and the modernisation and resilience components; and incorporating financial, project preparation, and implementation capacity into the transition from estimated needs to the achieved functional outcome. The approach to evaluating investment alternatives has also been further developed through the relationship "investment – function – time – risk – avoided losses," which shifts the selection criterion away from minimising initial expenditure towards assessing outcomes over the entire life cycle.

The practical significance of the proposed approach lies in its potential application at the stages of scenario testing, investment portfolio formation, and preliminary project prioritisation before proceeding to detailed feasibility assessment and engineering design. Depending on the level of governance, the following targeted recommendations can be proposed:

– The Cabinet of Ministers of Ukraine and central executive authorities should complement the criterion based on the scale of physical destruction with indicators of function criticality, the duration of functional deficit, substitutability, cascading potential, and the expected reduction in future risk.

– Sectoral ministries and critical infrastructure operators should establish sector-specific requirements for acceptable recovery time, redundancy, autonomy, physical and cyber protection, and should justify the resilience component of investment not through a universal coefficient, but on the basis of the characteristics of the specific function and infrastructure system concerned.

– Regional military administrations and local self-government authorities should align infrastructure projects with territorial planning, demographic changes, the spatial relocation of population and businesses, future demand, and the actual operational capacity of territories.

– International financial institutions, donors, and development banks should distinguish between financing for emergency recovery, functional adaptation, modernisation, and systemic transformation, while linking financial support to project readiness, expected functional outcomes, and the capacity of the project to reduce long-term risk.

– Private investors, banks, and insurance institutions should assess infrastructure projects with due consideration of life-cycle costs, the risk of repeated damage, mechanisms for guarantees and war-risk insurance, and the economic effects arising from reduced future losses.

The study has several limitations that define the boundaries within which its results should be interpreted. RDNA1–RDNA5 represent successive analytical snapshots rather than a homogeneous statistical time series: the assessments were prepared as of different dates, cover different durations of the war, and incorporate changes in sectoral boundaries, price parameters, and the treatment of needs that had already been met. The simulation parameters used in the study therefore serve a methodological rather than forecasting purpose. The RDNA infrastructure block constructed for the analysis was used solely to ensure comparability over time and should not be regarded as equivalent to Ukraine's legally defined critical infrastructure system. The proposed model also does not replace engineering analysis of individual facilities and, at this stage, does not incorporate a fully parameterised matrix of cross-sectoral interdependencies, empirically estimated probabilities of repeated damage, or sector-specific functions of avoided losses.

Future research should focus on testing the proposed scenario model using actual data from individual sectors of Ukraine's critical infrastructure. This will require the development of comparable dynamic data series reflecting the scale of damage, residual investment needs, volumes of financing, actual project implementation, and changes in the intensity of risks. Such an empirical database would make it possible to gradually replace conditionally specified scenario parameters with empirically grounded estimates and to determine more precisely how different strategic recovery trajectories affect the scale and dynamics of investment needs over the long term.

**Use of artificial intelligence**

During the preparation of this manuscript, the author used ChatGPT (OpenAI, GPT-5.6 Sol) to assist with the translation of the manuscript from Ukrainian into English and for subsequent language editing and stylistic refinement, including improvements in grammar, academic wording, clarity, consistency, and readability. Artificial intelligence was used exclusively as a language-support tool and was not used to formulate the research problem, research design, methodology, analytical framework, or scientific hypotheses; to perform data analysis, calculations, modelling, or statistical procedures; to generate or interpret the research results; or to develop the scientific conclusions. All AI-assisted translations and language revisions were carefully reviewed and verified by the author to ensure their accuracy and consistency with the original scientific meaning. The author takes full responsibility for the content and final version of the manuscript.

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