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RISK-SENSITIVE MODELING FRAMEWORK OF CIRCULAR ECONOMY DEVELOPMENT IN THE SYSTEM OF ECONOMIC SECURITY

РИЗИК-ЧУТЛИВА МОДЕЛЬ РОЗВИТКУ ЦИРКУЛЯРНОЇ ЕКОНОМІКИ В СИСТЕМІ ЕКОНОМІЧНОЇ БЕЗПЕКИ

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The circular economy is increasingly viewed as a strategic tool for enhancing economic security by reducing resource dependency, mitigating supply chain vulnerabilities, and strengthening systemic resilience. Its significance now extends beyond environmental sustainability to include macroeconomic stability and national security, especially amid global uncertainty and geopolitical fragmentation. Yet, most analytical approaches overlook multidimensional risks shaping circular economy performance, particularly in crisis-prone contexts. This article introduces an integrated framework linking circular economy development, risk dynamics, and economic security outcomes. It combines a system-based model of economic security covering financial stability, energy security, innovation potential, environmental safety, and social welfare with a risk matrix addressing economic, environmental, geopolitical, social, and technological factors. The framework supports risk-informed policy design, enabling the integration of circular strategies into broader resilience agendas under persistent uncertainty.

Keywords: circular economy; economic security; risk-based modeling; system approach; multidimensional risks; economic resilience; sustainable development; crisis and conflict economies.

Циркулярна економіка дедалі частіше розглядається як стратегічний інструмент зміцнення економічної безпеки шляхом зниження залежності від ресурсів, пом'якшення вразливостей ланцюгів постачання та покращення системної стійкості. В умовах глобальної невизначеності, дефіциту ресурсів та геополітичної фрагментації, її значення виходить за межі сталого розвитку, охоплюючи питання макроекономічної стабільності та національної безпеки. Проте наявні аналітичні підходи рідко враховують багатовимірні ризики, що визначають ефективність циркулярної економіки, особливо в кризових та конфліктних середовищах, де волатильність та деструктивні фактори посилюють системну крихкість. У статті пропонується заповнити цю прогалину шляхом розробки теоретичних засад, які прямо пов'язують розвиток циркулярної економіки та показники економічної безпеки з урахуванням динаміки ризиків. Запропонована концепція поєднує системну модель економічної безпеки, що охоплює фінансову стабільність, енергетичну безпеку, інноваційний потенціал, екологічну безпеку та соціальне благополуччя, з інтегрованою матрицею ризиків, яка включає економічні, екологічні, геополітичні, соціальні та технологічні чинники. Ризики формально вбудовуються в модель через два канали передачі: фактори збурення, що відображають реалізовані шоки, та ризик-залежні параметри ефективності, які відображають контекстну результативність механізмів циркулярної економіки. Такий двоканальний підхід дозволяє моделювати асиметричні та нелінійні ефекти конфігурацій ризиків на компоненти безпеки, демонструючи, що внесок ініціатив циркулярної економіки у зміцнення економічної безпеки значною мірою залежить від поточного ризикового середовища. Запропонована структура забезпечує методологічну основу для розробки політик з урахуванням ризиків, сприяючи інтеграції стратегій циркулярної економіки у ширші програми економічної безпеки в умовах тривалої невизначеності.

Ключові слова: циркулярна економіка; економічна безпека; моделювання на основі ризиків; системний підхід; багатовимірні ризики; економічна стійкість; сталий розвиток; економіки в умовах кризи та конфлікту.

Problem statement. The circular economy has increasingly been promoted as a strategic response to resource scarcity, environmental degradation, and economic vulnerability. In recent policy and academic discourse, circular economy initiatives are often presented as instruments capable of enhancing economic resilience and strengthening economic security. However, the analytical foundations supporting this claim remain fragmented, particularly in contexts characterized by persistent uncertainty, systemic shocks, and structural instability.

A central problem in the existing literature lies in the disconnect between circular economy modeling and risk analysis. While numerous studies assess circular economy development through composite indicators, efficiency metrics, or qualitative frameworks, risks are frequently treated as exogenous or contextual factors rather than as integral elements of the analytical structure. At the same time, economic security research typically relies on macro-level indicators and institutional assessments that do not explicitly account for circular economy dynamics. This separation limits the ability to evaluate how circular economy mechanisms perform under adverse conditions and how risk environments shape their contribution to economic security.

The problem becomes especially acute in crisis- and conflict-affected economies. Armed conflict, geopolitical instability, environmental degradation, and social disruption generate multidimensional and interacting risks that alter the effectiveness of long-term structural transformations. In such environments, circular economy strategies may simultaneously mitigate certain vulnerabilities, such as import dependence or resource shortages – while becoming constrained by technological, financial, or institutional risks. Analytical approaches that assume stability or linear adjustment are therefore insufficient for assessing the real potential of circular economy development under these conditions.

Another unresolved issue concerns the lack of formal integration between system-oriented risk analysis and dynamic models of economic security. Although systems thinking has been widely applied to conceptualize circular economy transitions, it is rarely translated into formal modeling frameworks capable of capturing risk propagation, interaction effects, and time-dependent outcomes. As a result, policymakers and researchers lack tools for scenario-based assessment, stress testing, and adaptive strategy design in the field of circular economy and economic security.

Analysis of recent research and publications. Recent research increasingly recognizes the circular economy as a systemic framework aimed at decoupling economic growth from resource consumption while enhancing environmental sustainability and long-term resilience. Foundational studies conceptualize circular economy as a transition from linear production-consumption models toward closed-loop systems that balance economic and ecological objectives [1; 2; 3]. At the policy level, this vision has been institutionalized through strategic initiatives such as the European Union's Circular Economy Action Plan and OECD monitoring frameworks, which emphasize resource efficiency, waste reduction, and sustainable value creation [4; 5].

A growing strand of literature extends circular economy analysis by incorporating risk and resilience perspectives. Studies highlight that circular transitions are constrained by economic volatility, technological barriers, institutional weaknesses, and supply chain disruptions [6; 7; 8]. More recent contributions explicitly apply risk-based and systems-thinking approaches to circular economy, demonstrating how uncertainties and interdependencies affect circular performance [9; 10; 11]. These works underscore the relevance of multidimensional risks but typically address them at the micro- or meso-level, focusing on firms, projects, or supply chains.

Parallel research streams in economic security, resilience, and institutional economics emphasize that macroeconomic stability and development trajectories are strongly shaped by external shocks, governance quality, and conflict-related disruptions [12; 13; 14]. Studies on social-ecological resilience and systems dynamics further stress the importance of feedbacks, path dependence, and adaptive capacity in complex economic systems [15; 16; 17]. In the context of armed conflict, recent international reports document severe environmental damage, supply chain fragmentation, and heightened uncertainty, particularly relevant for economies undergoing wartime transformation [18].

Highlighting previously unresolved parts of the problem. Literature reveals a conceptual gap – circular economy risks are predominantly analyzed in isolation from macro-level economic security models, while economic security frameworks rarely account for circular economy dynamics. Existing circular economy indicator systems and metrics focus on performance measurement rather than risk transmission mechanisms [19; 20]. This fragmentation limits the ability to assess how multidimensional risks alter the effectiveness of circular economy in strengthening economic security, especially in crisis and war-affected contexts.

Formulating the purposes of the article. The purpose of this article is to develop an integrated analytical framework that explicitly links circular economy development, multidimensional risk dynamics, and economic security outcomes. The study aims to conceptualize economic security as a system of interrelated components influenced by circular economy mechanisms; construct an integrated risk matrix that captures direct and indirect interactions between major categories of risks and economic security dimensions; and formally embed risk effects into a dynamic economic security model through disturbance terms and risk-dependent effectiveness parameters. By doing so, the article seeks to provide a methodological foundation for risk-sensitive analysis of circular economy strategies, with particular relevance for economies exposed to systemic shocks, crises, and post-conflict transformation.

Summary of the main research material. To analyze the role of the circular economy under conditions of heightened uncertainty, this study employs a dynamic model of economic security that captures the interaction between circular economy development and key security components over time. Economic security is conceptualized as a multidimensional system composed of several interrelated subsystems, each reflecting a critical domain of national resilience [21]. The model is specified as a system of equations:

$$\begin{cases} F_t = \mathrm{Base}_0^F + \mathrm{Eff}_1^F \cdot CE_t^F + \mathrm{Err}_t^F \\ P_t = \mathrm{Base}_0^P + \mathrm{Eff}_1^P \cdot CE_t^P + \mathrm{Err}_t^P \\ I_t = \mathrm{Base}_0^I + \mathrm{Eff}_1^I \cdot CE_t^I + \mathrm{Err}_t^I \\ E_t = \mathrm{Base}_0^E + \mathrm{Eff}_1^E \cdot CE_t^E + \mathrm{Err}_t^E \\ S_t = \mathrm{Base}_0^S + \mathrm{Eff}_1^S \cdot CE_t^S + \mathrm{Err}_t^S \end{cases} \quad (1)$$

where each equation represents the evolution of a specific component of economic security at time t.

The variables F_t, P_t, I_t, E_t and S_t denote, respectively, *financial stability, energy security, innovation potential, environmental safety,* and *social welfare.* Together, these components form an integrated representation of the overall economic security system.

The terms Base_0^k (for $k \in \{F, P, I, E, S\}$) reflect baseline structural conditions of each security component, capturing long-term institutional, macroeconomic, and structural characteristics that are not directly driven by circular economy dynamics in the short run.

The variables CE_t^k represent the intensity or effectiveness of circular economy development relevant to each security dimension. These may include, for example, circular investment flows, resource efficiency improvements, recycling capacity, innovation diffusion, or social engagement in circular practices. This structure allows CE impacts to differ across economic security components rather than assuming a uniform effect.

The parameters Eff_1^k measure the marginal contribution of circular economy development to each dimension of economic security. Importantly, these coefficients are not treated as fixed technological constants – instead, they reflect the institutional, technological, and geopolitical context in which circular economy mechanisms operate.

Finally, the disturbance terms Err_t^k capture deviations from expected trajectories caused by external shocks, structural disruptions, and risk materialization. These terms represent the influence of economic, environmental, geopolitical, social, and technological risks that are not explicitly modeled as deterministic factors but affect the system dynamically over time.

This formulation enables the circular economy to be analyzed not as an isolated policy domain, but as an endogenous driver within a broader economic security system. At the same time, the inclusion of disturbance terms provides a natural entry point for integrating risk dynamics into the model, allowing CE effects to vary depending on the surrounding risk environment. By structuring economic security as a system of interrelated equations, the model establishes a formal foundation for linking circular economy development, risk exposure, and security outcomes.

Integrated risk matrix. To operationalize the multidimensional nature of risks affecting CE development and economic security, this study employs an integrated risk matrix framework (table 1). The matrix is designed to capture both direct and indirect interactions between major categories of risks and the key components of economic security defined in the model.

The matrix is structured around five aggregated groups of risks: economic, environmental,

Table 1

Integrated matrix of risks for the development of the circular economy in the system of economic security of the state

Risk group ↓ / Security component →	Financial (F)	Energy (P)	Innovation (I)	Environmental (E)	Social (S)
Economic risks	**Direct**	**Direct**	Indirect	Indirect	Indirect
Environmental risks	Indirect	Indirect	Indirect	**Direct**	Indirect
Geopolitical risks	**Direct**	**Direct**	**Direct**	Indirect	Indirect
Social risks	Indirect	Indirect	Indirect	Indirect	**Direct**
Technological risks	Indirect	**Direct**	**Direct**	Indirect	Indirect

Source: compiled by the author

geopolitical, social, and technological risks. These groups reflect the dominant sources of uncertainty shaping circular economy dynamics in crisis-prone environments and correspond to distinct transmission channels through which risks influence economic security outcomes.

Rows of the matrix represent risk categories, while columns correspond to economic security components (F_t, P_t, I_t, E_t, S_t). Each cell of the matrix reflects the strength and nature of the influence exerted by a given risk group on a specific component of economic security. This structure allows for a differentiated assessment of vulnerability, acknowledging that risks do not affect all security dimensions uniformly.

Within the matrix, direct impacts are identified where a risk group exerts an immediate and structurally significant influence on a particular security component. For example, geopolitical risks directly affect productive security through supply chain disruptions and investment barriers, while environmental risks directly influence environmental security via pollution, land degradation, and resource depletion. These direct relationships define the primary transmission pathways of risk.

Indirect impacts capture secondary or mediated effects that occur through interactions between security components or through feedback loops within the system. For instance, geopolitical instability may indirectly affect social security by triggering labor migration or income instability, while technological risks may indirectly undermine financial security by reducing investment efficiency and innovation returns. Indirect effects are essential for understanding cascading risk dynamics and systemic vulnerability.

The logic of the matrix is inherently systemic – risks are not treated as isolated shocks but as interacting forces capable of reinforcing or dampening one another across economic security dimensions. This approach allows for the identification of risk clusters and synergistic effects, such as situations in which geopolitical shocks intensify economic volatility and technological stagnation simultaneously, amplifying their combined impact on circular economy performance.

By distinguishing between direct and indirect effects and explicitly mapping risk-security interactions, the integrated matrix serves as both an analytical and diagnostic tool. It enables comparative assessment across risk categories, supports prioritization of policy interventions, and provides a structured foundation for linking qualitative risk identification with the quantitative dynamics of the economic security model (1).

Linking the integrated risk matrix to the Economic Security model. The integrated risk matrix (table 1) serves as the analytical bridge between qualitative risk identification and the quantitative dynamics of the economic security model. This linkage is established through two complementary channels: risk-induced disturbances and risk-modified effectiveness of circular economy mechanisms.

Risks as disturbance terms (Err_t^k). First, risks identified in the matrix are mapped onto the disturbance terms Err_t^k of the economic security model. These terms capture the direct impact of realized risks on the evolution of each economic security component $k \in \{F, P, I, E, S\}$. For example, geopolitical shocks affecting supply chains and trade flows manifest as negative disturbances in productive and financial security, while environmental risks related to war-induced pollution directly influence environmental security dynamics. The disturbance term can be interpreted as a function of time-varying risk factors:

$$\mathrm{Err}_t^k = f(\mathrm{R}_t^{eco}, \mathrm{R}_t^{env}, \mathrm{R}_t^{geo}, \mathrm{R}_t^{soc}, \mathrm{R}_t^{tech}) \quad (2)$$

where R_t^{eco}, R_t^{env}, R_t^{geo}, R_t^{soc}, and R_t^{tech} denote economic, environmental, geopolitical, social, and technological risks, respectively.

In this interpretation, Err_t^k reflects both the intensity and timing of risk materialization. The integrated matrix guides the assignment of shocks by indicating which risk categories exert direct versus indirect influence on specific security components. Indirect effects may enter with delays or reduced magnitude, reflecting mediated transmission through other subsystems. This approach allows the model to capture asymmetric and nonlinear responses to external shocks without imposing restrictive assumptions on their functional form.

Risks as modifiers of Circular Economy effectiveness (Eff_1^k **).** Second, risks influence the parameters Eff_1^k, which measure the effectiveness of circular economy development in strengthening each component of economic security. Rather than treating these coefficients as fixed, the model allows them to vary depending on the prevailing risk environment.

For instance, high geopolitical or technological risks may reduce the capacity of circular investments to generate positive effects on energy security or innovative potential due to disrupted supply chains or limited access to advanced technologies. Conversely, under certain conditions, elevated economic or environmental risks may increase the relative effectiveness of circular practices by intensifying incentives for resource efficiency, substitution, and domestic value creation. In this sense, risks act as *contextual amplifiers or suppressors* of CE impacts.

The integrated matrix provides a structured basis for determining which risk categories are most likely to alter Eff_1^k for each security component. This enables differentiated parameter adjustment rather than uniform scaling, preserving the multidimensional nature of economic security. The effectiveness parameter of CE development is treated as a dynamic, state-dependent coefficient. Rather than adjusting instantaneously, Eff_1^k evolves over time in response to the prevailing risk environment, reflecting institutional inertia and path dependence. Formally, this can be expressed as:

$$\mathrm{Eff}_{1,t}^k = \mathrm{f}(\mathrm{Eff}_{1,t-1}^k, R_t) \quad (3)$$

where $R_t = \left\{R_t^{eco}, R_t^{env}, R_t^{geo}, R_t^{soc}, R_t^{tech}\right\}$ are risk factors influence the adjustment of effectiveness with a time lag.

The joint specification of Err_t^k and $\mathrm{Eff}_1^k(R_t)$ enables scenario analysis based on alternative risk configurations. Scenarios are defined by varying the intensity and combination of risk factors, allowing assessment of economic security trajectories under different stress conditions. This approach supports comparative evaluation of circular economy strategies and identification of conditions under which circular transitions remain resilient or become vulnerable.

Through this formal linkage, the integrated risk matrix is transformed from a descriptive classification tool into a dynamic modeling instrument. It provides a structured pathway for embedding multidimensional risk dynamics into the analysis of CE development and economic security.

Conclusions. This study develops an integrated analytical framework for assessing the role of the circular economy in strengthening economic security under conditions of heightened uncertainty and systemic risk. By combining a multidimensional economic security model with an integrated risk matrix, the paper addresses a key conceptual gap in the literature – namely, the absence of a formal linkage between circular economy dynamics, risk interaction, and economic security outcomes.

The proposed approach advances existing CE research in several respects. First, it conceptualizes economic security as a system of interrelated components: financial, energy, innovation, environmental, and social, thereby avoiding excessive aggregation and enabling differentiated impact analysis. Second, it explicitly incorporates multidimensional risks into the modeling framework through two complementary channels: disturbance terms capturing realized shocks and risk-dependent effectiveness parameters reflecting context-specific performance of circular economy mechanisms. This dual-channel integration allows the model to distinguish between temporary destabilization and structural erosion of circular economy effectiveness.

Importantly, the framework is particularly suited to crisis- and conflict-affected economies, where traditional assumptions of stability and gradual adjustment no longer hold. In such contexts, CE initiatives face both intensified constraints and heightened strategic relevance. The model captures this duality by allowing risks to simultaneously suppress and, under certain conditions, amplify the contribution of circular practices to economic security. This perspective challenges overly optimistic interpretations of CE as an inherently stabilizing solution and highlights the importance of risk-aware policy design.

From a policy standpoint, the framework supports the integration of CE objectives into broader economic security and resilience strategies. The explicit mapping of risk-security interactions enables targeted intervention, scenario-based stress testing, and prioritization of policy measures under adverse conditions. By moving beyond descriptive indicators toward a risk-sensitive analytical structure, the model provides a foundation for adaptive and context-specific circular economy governance.

Despite its conceptual contributions, this study has several limitations. First, the proposed framework is primarily theoretical and does not provide empirical estimation of model parameters. This choice is intentional, as the objective is to establish an analytically coherent structure capable of integrating multidimensional risks into circular economy analysis, rather than to deliver context-specific numerical results. Second, the risk matrix relies on aggregated risk categories, which may mask heterogeneity within individual risk types. However, such aggregation is necessary to maintain analytical tractability and to focus on systemic interactions rather than isolated events. Third, while the model allows for dynamic interpretation, it does not explicitly specify functional forms or lag structures, leaving room for future empirical and simulation-based extensions. These limitations do not undermine the validity of the framework but instead highlight its flexibility and potential for further development.

Future research may extend the proposed framework in several directions. Empirical calibration using national or sectoral data would allow quantitative estimation of risk impacts and effectiveness parameters. Dynamic extensions, including lag structures and feedback loops between economic security components, could further enhance realism. Additionally, integrating institutional and governance quality indicators may improve understanding of how policy capacity moderates the relationship between risk exposure and circular economy performance.

Overall, the study contributes to the evolving literature on circular economy and economic security by offering a flexible, theoretically grounded framework capable of capturing complexity, uncertainty, and systemic interaction. In doing so, it lays the groundwork for more robust assessment of CE strategies in environments shaped by persistent risk and structural disruption.

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