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ENTROPY AS AN INDICATOR OF ECONOMIC SECURITY FOR ASSESSING SYSTEM STABILITY

ЕНТРОПІЯ ЯК ІНДИКАТОР ЕКОНОМІЧНОЇ БЕЗПЕКИ ПІД ЧАС ОЦІНЮВАННЯ СТАБІЛЬНОСТІ СИСТЕМИ

The article examines entropy as an indicator of economic security for assessing system stability. Entropy is interpreted as a quantitative measure of uncertainty reflecting the variability, coherence, and internal structure of economic systems. The study applies an entropy-based approach to indicators of cybersecurity, innovation, and human development, enabling a multidimensional assessment of system stability and resilience. The results demonstrate that lower entropy values correspond to higher levels of stability, predictability, and controllability, while higher entropy indicates increased fragmentation, vulnerability, and systemic risk. The findings confirm that entropy can serve as a complementary analytical tool for assessing economic security and identifying hidden structural imbalances in economic systems.

Keywords: *economic security, entropy, system stability, systemic risk, uncertainty, economic resilience, cybersecurity.*

Пропоноване дослідження присвячене аналізу можливостей використання ентропії як індикатора економічної безпеки в оцінюванні стабільності економічних систем. Зростання невизначеності та ускладнення структури економічних процесів обмежує ефективність традиційних підходів до оцінювання економічної безпеки, які ґрунтуються переважно на макроекономічних і фінансових показниках і не відображають внутрішню варіативність системи. Ентропія інтерпретується як кількісна міра невизначеності, що характеризує ступінь розсіювання та неоднорідності станів економічної системи, відображаючи розподіл ймовірностей її можливих конфігурацій. У такому трактуванні ентропія дозволяє перейти від фіксації окремих показників до оцінювання внутрішньої структури системи, її збалансованості та узгодженості. Застосування ентропійного підходу дає змогу оцінити рівень впорядкованості економічних процесів, ступінь їх взаємозв'язку та керованості, що безпосередньо пов'язано зі станом економічної безпеки. Встановлено, що нижчі значення ентропії відповідають більш структурованим системам із відносно рівномірним розподілом ресурсів і функцій, узгодженістю інституційних механізмів і передбачуваністю розвитку. Такі системи характеризуються вищою здатністю до адаптації та збереження стабільності в умовах зовнішніх і внутрішніх збурень.

Натомість вищі значення ентропії свідчать про фрагментацію економічних процесів, асиметрію розвитку, зниження узгодженості між елементами системи та зростання невизначеності. Це супроводжується підвищенням рівня системних ризиків, ускладненням управління та зниженням стійкості економічної системи. Методичний підхід базується на застосуванні ентропійного аналізу до показників кібербезпеки, інноваційного розвитку та людського розвитку як ключових складових сучасної економіки. Це забезпечує багатовимірну оцінку економічної безпеки з урахуванням технологічних, інституційних і соціальних факторів. Результати дослідження свідчать про те, що ентропія відображає рівень внутрішньої узгодженості економічних систем і дозволяє виявляти структурні дисбаланси, які не фіксуються традиційними показниками. Зростання ентропії асоціюється з підвищенням системної вразливості, тоді як її зниження відповідає більш стабільному та керованому функціонуванню економічної системи.

Ключові слова: *економічна безпека, ентропія, стабільність системи, системні ризики, невизначеність, економічна стійкість, кібербезпека.*

Formulation of the problem. In the context of increasing systemic uncertainty, hybrid threats, and ongoing economic transformations, ensuring economic security has become a critical challenge for modern economies. Contemporary economic systems operate in environments characterized by complex, interconnected, and often non-linear risks, which complicates their timely identification and assessment.

Traditional approaches to assessing economic security are largely based on macroeconomic and financial indicators that reflect individual aspects of economic performance. However, these approaches do not fully capture the level of uncertainty and internal variability inherent in economic processes. As a result, they provide a limited understanding of system stability and its vulnerability to destabilizing influences.

Under such conditions, there is a growing need for analytical tools capable of reflecting not only the state of the system but also the degree of its order, coherence, and resilience. In this regard, entropy can be considered a promising methodological approach, as it allows for the measurement of uncertainty and heterogeneity within economic systems.

Analysis of recent research and publications. Contemporary research on economic security increasingly emphasizes the role of uncertainty, systemic risks, and structural interdependencies in shaping the stability of economic systems. Traditional approaches to economic security assessment have primarily relied on macroeconomic indicators; however, recent studies highlight the need to incorporate more complex analytical tools capable of capturing uncertainty and system variability.

A significant body of research focuses on the application of information theory and entropy as measures of uncertainty. Classical works by Miller G. [5] and Paninski L. [7] establish the methodological foundations for entropy estimation as a quantitative measure of uncertainty in complex systems. Further developments by Hausser J. [2] extend entropy-based approaches to systems characterized by nonlinear relationships and high-dimensional data structures. These studies demonstrate that entropy can serve as an effective analytical tool for assessing variability and unpredictability within economic systems.

In the context of economic risk and system stability, Savina N.B. et al. [9] show that entropy can be applied to evaluate business risks, interpreting it as an indicator of uncertainty in financial and economic environments. This approach provides a methodological basis for extending entropy analysis to broader economic security assessments.

At the same time, international indices such as the Global Innovation Index [1], the Human Development Index [3], and the National Cybersecurity Index [7] provide important empirical dimensions for analyzing the resilience and vulnerability of economic systems. These indices reflect key components of economic security, including innovation capacity, human capital development, and the ability to respond to technological and cyber threats.

Modern research also highlights the increasing importance of technological and institutional factors in ensuring economic security. In particular, cybersecurity is considered a critical element of national resilience, as it directly affects the stability of digital infrastructure and economic processes [6].

Despite these contributions, the use of entropy as an analytical tool for assessing economic security remains insufficiently developed. Existing studies primarily focus on entropy in risk analysis or isolated economic processes, while its potential for evaluating systemic economic security, particularly in relation to innovation, technological resilience, and cyber threats, has not been fully explored.

Formulation of the purpose of the articleis to assess the applicability of entropy as an analytical tool for evaluating economic security by interpreting it as a measure of systemic uncertainty in economic systems.

Presentation of the main material. In modern economic systems, uncertainty represents a fundamental characteristic that significantly influences the stability and security of economic processes. The increasing complexity of economic interactions, the presence of nonlinear effects, and the impact of external shocks require the use of analytical tools capable of capturing not only the state of the system but also the degree of its variability and unpredictability.

Entropy, originally developed within the framework of information theory, is widely used as a quantitative measure of uncertainty associated with the distribution of possible system states. Classical studies define entropy as an indicator of the level of disorder or unpredictability in a system, reflecting the probability distribution of its possible outcomes [5; 8]. In this context, entropy allows for the assessment of how dispersed or concentrated the states of a system are, which directly relates to the degree of its stability.

The application of entropy in economic analysis has expanded significantly in recent decades, particularly in the study of complex and nonlinear systems. Research by Hausser J. demonstrates the applicability of entropy-based methods in analyzing systems with high variability and multidimensional interactions [2]. These approaches provide a methodological basis for evaluating uncertainty in economic environments, where traditional deterministic models often fail to capture the full range of possible system behaviors.

In economic systems, entropy can be interpreted as a measure of heterogeneity and variability of economic processes. Higher entropy values indicate a greater degree of dispersion and unpredictability, which may reflect increased systemic risk and vulnerability. Conversely, lower entropy values are associated with more structured and coherent systems, characterized by greater predictability and stability.

From the perspective of economic security, uncertainty acts as a key transmission mechanism of risk. The relationship between uncertainty, risk, and economic security can be understood as a sequential chain, where increasing uncertainty leads to higher levels of risk, which in turn may weaken the stability and resilience of economic systems. In this regard, entropy serves not only as a statistical measure but also as an analytical indicator that reflects the level of systemic vulnerability.

The relevance of entropy for economic security analysis is further supported by studies that apply entropy-based approaches to risk assessment in economic systems. In particular, Savina N.B. et al. demonstrate that entropy can be effectively used to evaluate business risks by capturing the uncertainty inherent in economic processes [9]. This confirms the potential of entropy as a tool for extending risk analysis to broader assessments of economic security.

The growing complexity of economic systems and the increasing impact of systemic and hybrid threats necessitate the use of analytical approaches that go beyond traditional macroeconomic indicators. In this context, entropy can be interpreted as an indicator that reflects the level of uncertainty, variability, and structural coherence of economic systems.

Unlike conventional indicators that capture static or partial characteristics of economic performance, entropy provides a dynamic measure of system organization. It allows for the assessment of how evenly or unevenly economic processes and parameters are distributed within a system. This makes entropy particularly relevant for analysing economic security, which depends not only on current performance but also on the stability and predictability of system behaviour.

From the perspective of economic security, entropy can be interpreted through the relationship between uncertainty and risk. Higher entropy values indicate greater dispersion of system states and a higher degree of unpredictability, which may lead to increased vulnerability to external and internal shocks. In such conditions, economic systems become less controllable and more sensitive to destabilizing influences. Conversely, lower entropy values reflect a higher degree of system organization and coherence, which contributes to greater stability and resilience.

This interpretation aligns with the understanding of uncertainty as a key factor influencing economic risk and security [5; 8]. Entropy, therefore, can be considered not only as a statistical characteristic but also as an analytical indicator of systemic risk within an economic environment.

At the same time, it is important to note that traditional approaches to economic security assessment often rely on isolated indicators such as GDP growth, inflation, or financial stability metrics. While these indicators provide valuable information, they do not capture the internal variability and structural heterogeneity of economic systems. As a result, they may underestimate latent risks that accumulate within the system.

In contrast, entropy allows for the identification of hidden imbalances and structural inconsistencies that are not reflected in standard economic indicators. This makes it a useful complementary tool for economic security analysis, particularly in environments characterized by high uncertainty and rapid transformation.

Furthermore, the application of entropy-based approaches in economic research has already demonstrated its effectiveness in risk assessment and analysis of complex systems [2; 9]. Extending this approach to the evaluation of economic security provides an opportunity to develop more comprehensive and adaptive analytical frameworks.

Thus, entropy can be interpreted as an additional indicator of economic security, reflecting the level of uncertainty, structural variability, and systemic vulnerability of economic systems.

To evaluate the level of uncertainty in economic systems, this study applies an entropy-based approach grounded in the principles of information theory. Entropy is used as a quantitative measure that reflects the distribution of possible system states and the degree of their unpredictability.

The estimation of entropy is based on the Shannon formulation, which can be represented as:

$$H = -\sum_{i=1}^{n} p_i log_2 p_i , \qquad (1)$$

where: H – entropy of the system; p_i – probability of the i-th state of the system; n – total number of possible states.

This expression reflects the average level of uncertainty associated with the system. Entropy reaches its maximum when all states are equally probable, and decreases as the distribution becomes more concentrated.

In practical applications, the probabilities i are derived from empirical data. They can be estimated based on the relative distribution of indicators, normalized values, or statistical measures such as variance and standard deviation. This allows transforming observed economic indicators into a probabilistic structure suitable for entropy calculation.

For systems where all states are equally likely, entropy reaches its theoretical maximum:

$$H_{max} = log_2 n$$

This value serves as a benchmark for interpreting the level of uncertainty within the system. The closer the calculated entropy is to N_{max}, the higher the degree of dispersion and unpredictability.

From the perspective of economic security, entropy is interpreted as an indicator of systemic uncertainty. Higher values of entropy correspond to greater heterogeneity and reduced controllability of economic processes, which may indicate increased vulnerability. Lower entropy values, in contrast, reflect a more ordered structure and greater predictability, which are associated with higher levels of stability.

Thus, the entropy-based methodological approach enables the quantification of uncertainty in economic systems and provides a basis for comparative analysis of their security and resilience.

The empirical analysis is based on the application of the entropy approach to key dimensions of economic systems, including cybersecurity, innovation, and human development. The entropy values used in this study are derived from calculations presented in the authors' previous research, where the methodology and data processing procedures are described in detail [6]. In this study, these results are reinterpreted in the context of economic security.

To systematize the obtained results, entropy values are analyzed in terms of their implications for system coherence, predictability, and vulnerability (Table 1).

The results demonstrate that entropy values provide a meaningful basis for distinguishing between more structured and more fragmented economic systems. Lower entropy corresponds to higher levels of organization and predictability, which are essential for maintaining economic security. In contrast, higher entropy reflects increased variability and systemic uncertainty, indicating potential vulnerabilities.

In the cybersecurity domain, lower entropy values are associated with coordinated institutional frameworks and consistent policy implementation, which reduce exposure to cyber threats. Higher entropy, on the contrary, indicates fragmentation and a lack of coherence, increasing the risk of system disruption.

A similar pattern is observed in innovation systems. Lower entropy reflects a more structured and efficient innovation environment, contributing to economic stability and competitiveness. Higher entropy suggests dispersed and inconsistent innovation strategies, which may weaken system effectiveness and increase uncertainty.

In terms of human development, lower entropy indicates a more balanced distribution of human capital and social resources, which supports system resilience. Higher entropy reflects structural disparities and uneven development, which may increase socio-economic risks and reduce stability.

Overall, the empirical analysis confirms that entropy can be interpreted as an indicator of economic security. Systems characterized by lower entropy demonstrate higher levels of coherence, controllability, and resilience, while higher entropy values are associated with increased vulnerability and systemic risk.

Table 1

Entropy-based assessment of economic security

Dimension	Low Entropy (↓H)	High Entropy (↑H)	Implication for Economic Security
Cybersecurity	Coordinated policies, standardized responses	Fragmented systems, inconsistent protection	Lower vulnerability / Higher vulnerability
Innovation	Structured innovation system, efficiency	Dispersed strategies, lack of coherence	Higher stability / Lower predictability
Human Development	Balanced human capital distribution	Uneven development, structural gaps	Higher resilience / Increased social risk
Overall system	High coherence, controllability	High variability, instability	Strong economic security / Weak economic security

Source: developed by the authors based on empirical entropy calculations

The obtained entropy values allow for a structured interpretation of economic systems in terms of their level of security, stability, and vulnerability. Within the proposed approach, entropy reflects the degree of uncertainty and internal variability of the system, which directly influences its capacity to maintain stable functioning under external and internal pressures.

Lower entropy values indicate a higher level of system organization and coherence. Such systems are characterized by more predictable behavior, coordinated institutional mechanisms, and a balanced distribution of key parameters. From the perspective of economic security, this corresponds to higher controllability and resilience, as the system is better able to respond to disturbances and maintain stability.

In contrast, higher entropy values reflect increased dispersion and heterogeneity of system elements. This indicates a lack of coordination, structural imbalances, and a higher degree of uncertainty. In such conditions, economic systems become more sensitive to shocks, and their ability to absorb disturbances decreases, which leads to higher systemic risk [4].

The comparative analysis shows that systems with lower entropy across multiple dimensions, particularly in cybersecurity and innovation, demonstrate stronger positions in terms of economic security. These systems are characterized by more consistent policy implementation, higher efficiency of resource allocation, and greater adaptability to changing conditions.

At the same time, elevated entropy values signal areas of potential vulnerability. In the cybersecurity domain, higher entropy reflects fragmentation of protection mechanisms and increased exposure to digital threats. In innovation systems, it may indicate a lack of strategic coherence, reducing overall effectiveness. In the social and human development dimension, higher entropy points to structural disparities that can weaken long-term stability.

Thus, entropy values make it possible to identify not only the current state of economic systems but also latent risks associated with their internal structure. The proposed approach enables the differentiation of more secure and more vulnerable systems based on their degree of organization and predictability, providing an additional analytical tool for economic security assessment.

Conclusions. The conducted study allows considering entropy as a meaningful analytical tool for assessing economic security through the measurement of systemic uncertainty. In contrast to traditional macroeconomic indicators, entropy reflects the internal structure of economic systems, capturing the degree of variability, coherence, and predictability of their functioning.

The results indicate that lower entropy values correspond to more organized and stable systems characterized by higher levels of controllability and resilience. Such systems are better able to maintain functionality under conditions of external and internal disturbances. Conversely, higher entropy values reflect increased heterogeneity and fragmentation, which are associated with reduced predictability and higher vulnerability to destabilizing influences.

The empirical analysis demonstrates that key dimensions of economic systems, including cybersecurity, innovation, and human development, exhibit different levels of entropy that influence the overall level of economic security. More coordinated and structurally consistent systems tend to demonstrate lower entropy, while systems with dispersed and unbalanced characteristics are associated with higher uncertainty and risk.

The findings also show that entropy allows identifying latent vulnerabilities that are not fully captured by conventional indicators. This makes it possible to detect potential threats to economic security at earlier stages, particularly in environments characterized by rapid transformation and increasing complexity.

Thus, the application of an entropy-based approach expands the methodological toolkit of economic security analysis and provides a basis for more comprehensive assessment of system stability, resilience, and vulnerability under conditions of uncertainty.

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