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AN ECONOMETRIC ANALYSIS OF THE DIFFERENTIATED IMPACT OF CIRCULAR ECONOMY DEVELOPMENT ON ECONOMIC SECURITY IN POLAND

This article empirically examines the relationship between circularity development and economic security in Poland over the 2000-2023 period. Using correlation analysis, stationarity testing, VAR and VECM modelling, Toda-Yamamoto Granger causality, and impulse response analysis, the study examines how the circular economy interacts with five components of economic security: financial, energy, innovation, environmental, and social. Results reveal a differentiated effect varying in direction, magnitude, and time horizon: energy security shows a stable positive long-run relationship; social security co-moves with this equilibrium passively; innovation and environmental security combine positive long-run correlation with negative short-run dynamics; financial security shows the weakest, least stable relationship. The findings suggest that the relationship is primarily driven by long-run structural adjustment.

Keywords: *circular economy, economic security, econometric modelling, VAR/VECM modelling, cointegration, Granger causality, impulse response analysis, Poland.*
JEL classification: *C01, C32, Q56.*

ЕКОНОМЕТРИЧНИЙ АНАЛІЗ ДИФЕРЕНЦІЙОВАНОГО ВПЛИВУ РОЗВИТКУ ЦИРКУЛЯРНОЇ ЕКОНОМІКИ НА ЕКОНОМІЧНУ БЕЗПЕКУ ПОЛЬЩІ

Метою статті є емпірична перевірка впливу розвитку циркулярної економіки на структурні складові економічної безпеки держави на прикладі Республіки Польща за період 2000-2023 рр. Актуальність дослідження обумовлена тим, що, попри активне поширення концепції циркулярної економіки в межах Європейського Союзу як інструменту підвищення ресурсної незалежності та довгострокової конкурентоспроможності, особливості її взаємозв'язку з окремими складовими економічної безпеки залишаються недостатньо дослідженими в кількісному вимірі, а наявні теоретичні підходи потребують подальшої емпіричної апробації на реальних часових рядах.

У дослідженні застосовано послідовність економетричних методів: кореляційний аналіз для попереднього виявлення характеру взаємозв'язку між циркулярною економікою та кожною зі складових економічної безпеки (фінансовою, енергетичною, інноваційною, екологічною, соціальною); тест Дікі-Фуллера для перевірки стаціонарності часових рядів; модель векторної авторегресії; модель векторної корекції помилок у поєднанні з тестом Йогансена; тест причинності Грейнджера у специфікації Тода-Ямамото; аналіз функцій імпульсного відгуку для визначення динаміки реакції кожної складової на шок розвитку циркулярної економіки.

Результати дослідження засвідчили, що вплив розвитку циркулярної економіки на економічну безпеку є неоднорідним не лише за силою, а й за напрямом та часовим горизонтом реалізації. Для енергетичної безпеки встановлено стійкий позитивний довгостроковий взаємозв'язок із значущим коригуванням до рівноваги. Соціальна безпека демонструє спільний рух із довгостроковою рівновагою системи, однак це коригування забезпечується переважно іншими складовими, а не власною динамікою. Інноваційна та екологічна безпека виявили розбіжність між часовими горизонтами – обидві складові позитивно корелюють із циркулярною економікою у довгостроковій перспективі, проте демонструють стійку від'ємну короткострокову динамічну реакцію, що свідчить про наявність короткострокових адаптаційних витрат структурної трансформації. Фінансова безпека продемонструвала найслабший і найменш стійкий взаємозв'язок зі зміною знаку реакції в межах досліджуваного горизонту. Для жодної складової не виявлено статистично значущої короткострокової причинності за Грейнджером, що вказує на реалізацію взаємозв'язку переважно через довгострокові структурні

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механізми.

Практична цінність отриманих результатів полягає у формуванні емпіричного підґрунтя для диференційованого підходу до формування політики розвитку циркулярної економіки з урахуванням специфіки впливу на окремі складові економічної безпеки.

Ключові слова: *циркулярна економіка, економічна безпека, економетричне моделювання, VAR/VECM-моделювання, коінтеграція, причинність Грейнджера, аналіз функцій імпульсного відгуку, Польща.*

Introduction (Problem Statement). Ensuring economic security has become a practical imperative rather than a purely academic concern for economies exposed to sustained structural shocks, including war-related disruption, supply chain fragmentation, and resource scarcity. At the same time, circular economy (CE) principles have gained substantial traction across the European Union as a strategy for reducing resource dependency, strengthening long-term competitiveness, and building structural resilience. Yet the relationship between circular economy development and components of economic security remains insufficiently quantified – existing research tends to treat circular economy either as a narrowly environmental or resource-efficiency agenda, or as a general contributor to sustainability, without disaggregating its effect across the distinct structural dimensions of economic security or examining whether this effect operates in the short or the long run.

A theoretical model linking circular economy development to a five-component structure of economic security (financial, energy, innovation, environmental, and social) was proposed in an earlier study [1], which explicitly identified the empirical validation of this framework using real time-series data as a necessary next step. The present study addresses this gap by applying the proposed framework to Poland, an EU economy with a comparatively mature institutional environment for circular economy implementation and a sufficiently long, continuous time series (2000-2023) for both circular economy performance and the five economic security components. This makes Poland a suitable empirical case for establishing whether, in which direction, and over what time horizon circular economy development is statistically associated with each dimension of economic security.

Analysis of Recent Research and Publications. The circular economy has been widely documented as a strategic response to resource scarcity, supply chain disruption, and climate risk, with the European Union positioning CE principles as a core pillar of long-term competitiveness and sustainability [2, 3].

For developing and transition economies, including Ukraine, international organizations have emphasized the need to link circularity indicators directly to broader economic resilience objectives. UNIDO's baseline assessment of circular economy development for Ukraine's industrial sector proposes a «triple nexus» approach that jointly considers sectoral development, circular economy performance, and systemic resilience, combining conventional CE indicators (material productivity, circular material use rate, energy intensity, waste generation) with indicators of innovation activity, employment structure, resource dependency, and resilience to external shocks [4]. This approach illustrates a broader shift in the literature: circular economy indicators increasingly overlap with, and are treated as informative for, the structural components of economic security, even though no single, universally adopted indicator system yet spans both domains. This growing attention to economic security is echoed at the EU policy level, where a dedicated strategy has recently identified economic security as a distinct strategic priority spanning multiple interconnected domains [5]. Reflecting on this recognition, economic security has been conceptualized in an earlier study as a multidimensional construct integrating financial, energy, innovation, environmental, and social dimensions [6].

Given that Poland serves as the empirical reference country for this study, particular attention was paid to research examining CE within the Polish context. Cader, Koneczna, and Marciniak [7] developed a regional CE indicator framework for the Wielkopolska region, addressing the challenge of monitoring CE progress below the national level. Nowaczek, Dziobek, and Kulczycka [8] examined the benefits and limitations of indicators used to monitor Poland's CE transformation in the context of national and EU strategic obligations. Ćwiklicki, Mirzyńska, and Żabiński [9] analyzed the institutionalization of CE within Polish regional development strategies through an adaptive governance lens. Most recently, Czaplicka-Kotas and Kulczycka [10] examined the regulatory implementation of CE principles in Poland's plastic packaging sector. Taken together, this body of work demonstrates a mature and actively developing national research agenda on CE monitoring and governance in Poland, though it remains focused on indicator design, regulatory implementation, and governance rather than on the econometric relationship between CE development and economic security.

The unresolved part of the problem addressed in the present study is therefore twofold. First, existing empirical literature on circular economy impacts tends to assess indicator design, governance, or regulatory implementation rather than disaggregating the dynamic econometric effect of circular economy development across the distinct structural components of economic security. Second, limited empirical evidence is available regarding the dynamic relationships between circular economy development and individual components of economic security, while the previously proposed theoretical CE-to-ES framework [1] has yet to be comprehensively examined using time-series econometric methods.

This study addresses both gaps through a component-by-component econometric analysis (correlation, stationarity, VAR/VECM, Granger causality, and impulse response analysis) applied to Poland.

Purpose and objectives of the article. The purpose of this article is to empirically validate the theoretical model linking circular economy development to the structural components of economic security proposed in an earlier study [1], using time-series data for Poland (2000-2023).

Research methods. To achieve the stated purpose, the study combines general theoretical and specific economic-statistical methods. General theoretical methods of abstraction, comparison, and generalization were applied to synthesize the differentiated findings across the five economic security components into an overall conclusion. Among the specific economic-statistical methods, the statistical method was used to process the underlying time-series data. The index method was applied to construct the composite indices of economic security and the circular economy. Correlation-regression analysis was used to identify the character of the relationship between circular economy development and each economic security component. The method of economic-mathematical modelling (including time-series stationarity, cointegration, and causality analysis) was applied to establish the dynamics of this relationship.

Main Results of Research. The empirical analysis proceeds in five stages, moving from a descriptive overview of co-movement and stationarity properties to a differentiated assessment of how circular economy development affects each component of economic security in Poland. All calculations and figures were produced in Python, using pandas and numpy for data handling, statsmodels for stationarity testing, VAR/VECM estimation, cointegration, Granger causality analysis, and impulse response analysis, and matplotlib/seaborn for visualization.

Result 1 – correlation and stationarity overview. Pearson correlation coefficients between the CE and each of the five economic security components, alongside the results of the ADF-test unit root test for all six series are reported in (tab. 1).

Table 1

Correlation and stationarity results

Component	Pearson correlation with CE	ADF conclusion
Financial security (F)	-0.153	Stationary
Energy security (P)	0.926	Non-stationary
Innovation security (I)	0.904	Stationary
Environmental security (E)	0.521	Non-stationary
Social security (S)	0.874	Non-stationary
Circular economy (CE)	–	Non-stationary

Source: calculated by the author.

Two features of these results shape the subsequent modelling strategy. First, correlation coefficients vary substantially in both magnitude and sign, ranging from a weak negative association for financial security (-0.153) to a strong positive association for energy security (0.926). This heterogeneity is a first indication that circular economy development does not exert a uniform influence across the components of economic security. Second, the stationarity results split the system into two distinct groups: F and I are integrated of order zero, while P, E, S, and CE are integrated of order one. Because a valid VAR requires all included series to share the same order of integration, this split determines the two separate modelling tracks pursued in Results 2 and 3: a stationary VAR system for (F, I, CE) and a cointegration-based VECM system for (P, E, S, CE).

Result 2 – stationary subsystem: VAR(F, I, ΔCE). Because F and I are stationary while CE is integrated of order one, the two stationary series were modelled jointly with the first difference of the circular economy index, ΔCE, rather than with CE in levels. This substitution restores the equal-integration-order condition required for a valid VAR specification while preserving the interpretability of the CE-related coefficients as an effect of circular economy growth rather than of its level. Lag order selection via AIC, BIC, HQIC, and FPE unanimously indicated a first-order specification, VAR(1). The estimated system is reported in (tab. 2).

Table 2

VAR(1) coefficient estimates for the (F, I, ΔCE) subsystem

Regressor	F equation	I equation	ΔCE equation
Constant	0.285	0.135	-0.032
F(t-1)	0.472 ($t = 2.15$, $p = 0.031$)	-0.173	0.056
I(t-1)	-0.024	1.014 ($t = 20.21$, $p < 0.001$)	0.022
ΔCE(t-1)	-0.426	-0.390	0.164

Source: calculated by the author.

The autoregressive coefficient of innovation security (1.014) indicates a markedly persistent process, while financial security shows moderate persistence (0.472). Neither F nor I displays a statistically significant contemporaneous response to lagged ΔCE at conventional levels, though the sign of the ΔCE coefficient is negative in both equations.

Stability of the estimated system was assessed via the roots of the companion matrix. Two roots (moduli of 3.06) satisfy the stability condition, but one root has a modulus of 0.984, falling just short of the boundary required for stability. This is attributable to the near-unit-root persistence of the innovation security series itself, with the univariate ADF test rejecting the unit root hypothesis for I only narrowly relative to the critical value, rather than to a misspecification of the ΔCE substitution. This finding is reported as a limitation of the model's short-run dynamic interpretation rather than as grounds for respecifying the system further.

The IRF of F and I to a shock in ΔCE over a ten-period horizon are presented in (fig. 1).

The response of financial security is negative in the initial periods, reaching -0.426 at h=1, before turning positive from approximately the sixth period onward and stabilizing near 0.020 by the tenth period. The response of innovation security is negative throughout the horizon, moving from -0.390 at h=1 to a stable level of approximately -0.33 by h=10, without evidence of a monotonically widening effect.

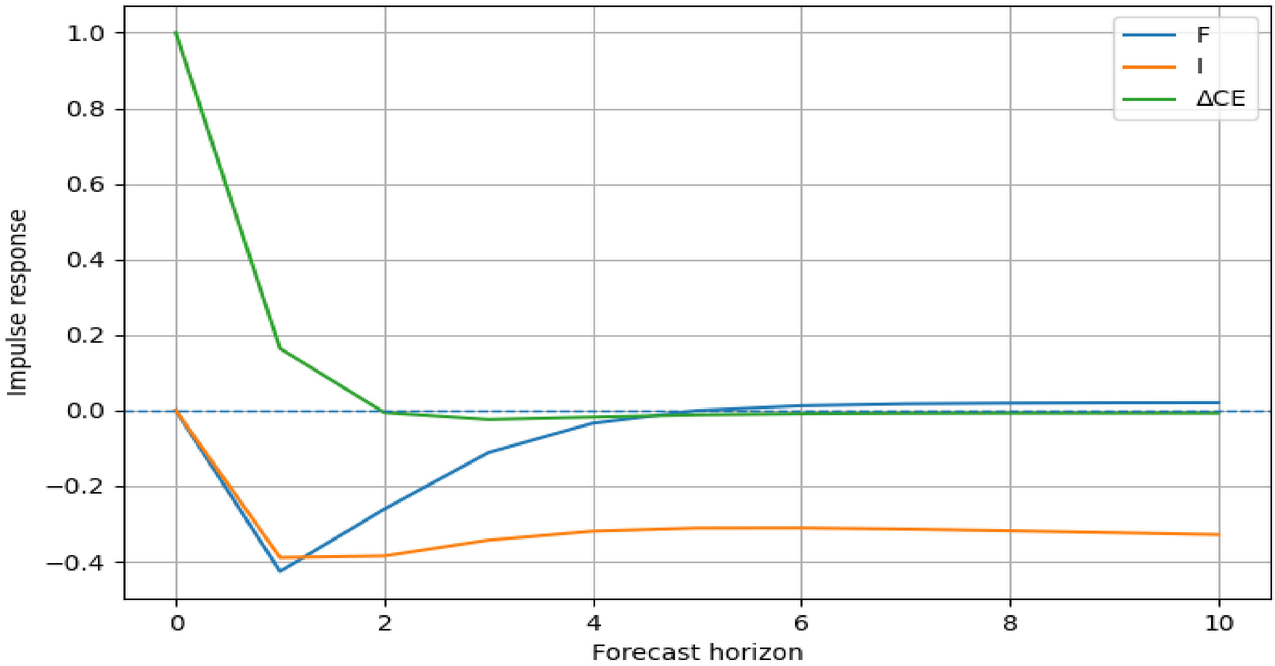

Fig. 1 Impulse response to a shock in circular economy growth (VAR) – F, I, ΔCE
Source: author's calculations and visualization.

These results indicate a delayed, sign-reversing response of financial security to circular economy growth, and a persistent, negative short-run response of innovation security, which contrasts with the strong positive correlation between I and CE reported in (tab. 2) – a divergence attributable to a shared long-run trend coexisting with an adverse short-run adjustment dynamic.

Result 3 – cointegrated subsystem: Johansen and VECM (P, E, S, CE). For the four non-stationary series the Johansen trace and maximum-eigenvalue tests identified a single cointegrating relationship (rank = 1), justifying a VECM rather than a VAR in levels or first differences. Lag order selection indicated a second-order specification. The error correction term (ECT) coefficients (tab. 3) capture the speed at which each variable adjusts back toward the long-run equilibrium relationship following a deviation.

Table 3

VECM error correction term (ECT/adjustment) coefficients

Component	**ECT coefficient (α)**	**z-statistic**	**p-value**
Energy security (P)	0.412	4.751	< 0.001
Environmental security (E)	1.370	4.288	< 0.001
Social security (S)	-0.014	-0.081	0.935
Circular economy (CE)	0.237	1.652	0.099

Source: calculated by the author.

Adjustment toward the long-run equilibrium is statistically significant for P and E, but not for S or CE. This asymmetry indicates that, while all four variables participate in a single cointegrating relationship (identified by the cointegrating vector P - 1.101·E - 0.101·S - 0.257·CE), the error-correcting adjustment following a deviation from this equilibrium is driven primarily by P and E, rather than by an independent correcting response of S.

The IRF of P, E, and S to a shock in CE over a ten-period horizon are presented in (fig. 2). Unlike the stationary VAR subsystem in Result 2, none of the three responses decays toward zero; instead, each converges to a non-zero plateau. This is the expected behaviour for a cointegrated system with a single cointegrating vector among four variables: three common stochastic trends remain in the system, so a shock to CE generally has a permanent, rather than transitory, effect on the levels of P, E, and S.

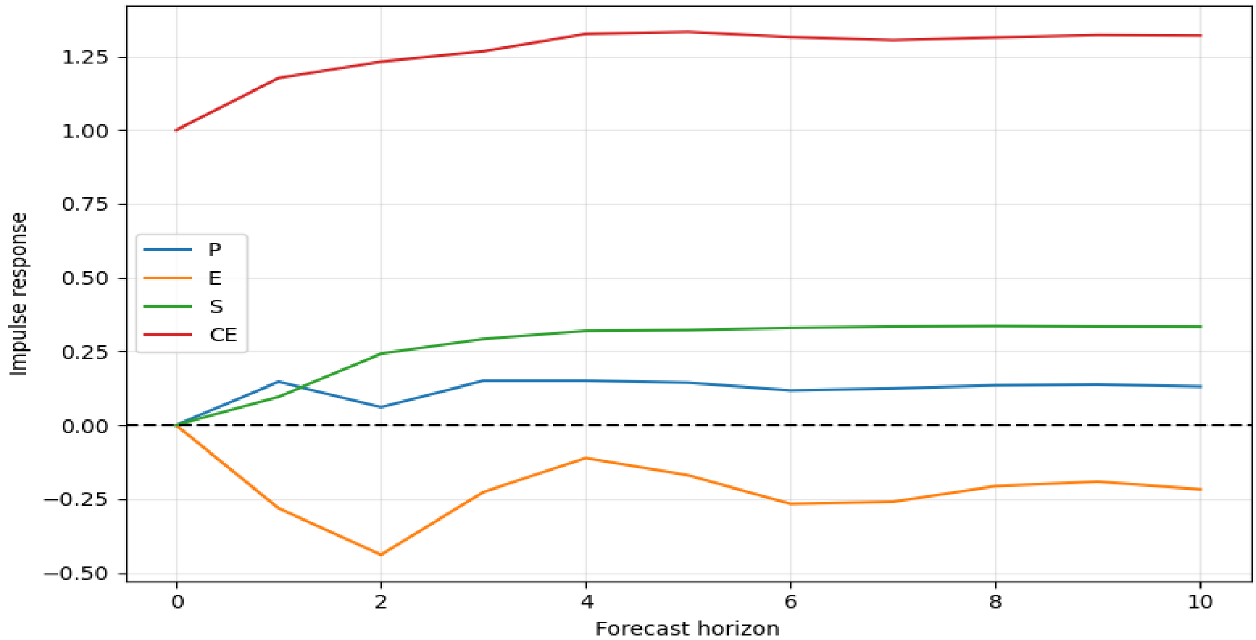

Fig. 2 Impulse response to a shock in circular economy development (VECM) – P, E, S, CE
Source: author's calculations and visualization.

The response of energy security (P) is positive throughout the horizon, stabilizing near 0.13 by the tenth period. Environmental security (E) shows the largest-magnitude response of the three: an initial negative dip, reaching approximately -0.44 at h=2, followed by partial recovery and stabilization near -0.22. Social security (S) shows a positive, gradually strengthening response that stabilizes near 0.33; however, given the statistically insignificant ECT coefficient reported in (tab. 4), this response reflects that S shows passive participation in the shared long-run equilibrium (via the cointegrating vector), rather than an independent error-correcting adjustment of S itself, which is instead driven primarily by P and E. Combined with the correlation results in (tab. 2) (P: 0.926; E: 0.521; S: 0.874) and the absence of significant Granger causality reported in Result 4, these patterns are consistent with a long-run structural relationship between circular economy development and each of these three components, though the underlying adjustment mechanism differs: P and E adjust to the equilibrium directly, while S co-moves with it.

Result 4 – Toda-Yamamoto Granger causality. The results of Toda-Yamamoto Granger causality tests for all five directions from circular economy development to the components of economic security (tab. 4).

Table 4

Toda-Yamamoto Granger causality test results (CE → component)

Direction	**χ^2 statistic**	**p-value**	**Conclusion**
CE → F	1.6923	0.4291	Not significant
CE → P	0.7294	0.6944	Not significant
CE → I	1.2248	0.5420	Not significant
CE → E	0.0218	0.9892	Not significant
CE → S	2.3390	0.3105	Not significant

Source: calculated by the author.

None of the five tested directions yields a statistically significant result at the 5% level; p-values range from 0.31 to 0.99. This indicates the absence of short-run predictive (Granger) causality from circular economy development to any of the five economic security components over the sample period. This finding is not inconsistent with the cointegration results reported in Result 3: the absence of Granger causality concerns short-run predictive content, whereas cointegration reflects a long-run equilibrium relationship that does not require one variable to Granger-cause another in the short run. Taken together with the correlation and IRF evidence from Results 1-3, the overall pattern suggests that, where a relationship between circular economy development and a given component of economic security exists, it operates through long-run structural adjustment (P, E) or shared trend co-movement (S), rather than through short-term predictive dynamics.

Result 5 – synthesis: the differentiated effect of circular economy development across economic security components. The results per component of economic security are consolidated in (tab. 5).

The central finding is that the effect of circular economy development on economic security is differentiated not only in magnitude, but in direction and mechanism, depending on the time horizon considered. For energy security, the relationship is unambiguously positive at both the correlation and the dynamic (error-correcting) level. For social security, the positive long-run co-movement is confirmed, but it is not driven by an independent adjustment of social security itself. For innovation and environmental security, the two horizons point in opposite directions: both show a strong positive long-run correlation with circular economy development, yet both display a negative, persistent short-run dynamic response – an outcome consistent with the interpretation that structural adaptation to circular economy transformation carries a short-run adjustment cost that coexists with a positive long-run trend. Financial security shows neither a stable direction nor a significant dynamic relationship, and its response even reverses sign within the observed horizon. No component displays statistically significant short-run Granger causality from circular economy development. Together, these results indicate that a uniform, single-mechanism policy approach to leveraging circular economy development for economic security is unlikely to be effective; the appropriate policy horizon and expected direction of effect differ by component.

Table 5

Summary of the relationship between circular economy development and economic security components

<table>
<tr><th>Component</th><th>Pearson correlation</th><th>ECT significance</th><th>Granger (TY)</th></tr>
<tr><td colspan="4">VAR (F, I, ΔCE) Subsystem</td></tr>
<tr><td>Financial (F)</td><td>-0.153</td><td>– (stationary system)</td><td>Not significant</td></tr>
<tr><td colspan="4">Short-run dynamic response:
Sign-reversing: negative initially, turning positive from h≈6, stabilizing near +0.02
Overall characterization:
Weakest and least stable relationship; direction is horizon-dependent</td></tr>
<tr><td>Innovation (I)</td><td>0.904</td><td>– (stationary system)</td><td>Not significant</td></tr>
<tr><td colspan="4">Short-run dynamic response:
Negative throughout, stabilizing near -0.33
Overall characterization:
Positive long-run co-trend, but a persistent negative short-run adjustment cost</td></tr>
<tr><td colspan="4">VECM (P, E, S, CE) Subsystem</td></tr>
<tr><td>Energy (P)</td><td>0.926</td><td>Significant (p < 0.001)</td><td>Not significant</td></tr>
<tr><td colspan="4">Short-run dynamic response:
Positive throughout, stabilizing near +0.13
Overall characterization:
Positive long-run structural relationship with significant equilibrium adjustment</td></tr>
<tr><td>Environmental (E)</td><td>0.521</td><td>Significant (p < 0.001)</td><td>Not significant</td></tr>
<tr><td colspan="4">Short-run dynamic response:
Negative throughout, stabilizing near -0.22
Overall characterization:
Counterintuitive: significant long-run cointegration and positive correlation, but an inertial, negative short-run effect of structural transformation</td></tr>
<tr><td>Social (S)</td><td>0.874</td><td>Not significant (p = 0.935)</td><td>Not significant</td></tr>
<tr><td colspan="4">Short-run dynamic response:
Positive throughout, stabilizing near +0.33
Overall characterization:
Passive co-movement with the system's long-run equilibrium, driven by P and E rather than by S's own adjustment</td></tr>
</table>

Source: compiled by the author.

Conclusions. This study provided an empirical validation, for Poland over 2000-2023, of the theoretical model linking circular economy development to the five structural components of economic security proposed in an earlier study [1]. The central finding is that this relationship is differentiated rather than uniform – not only in magnitude, but in direction and in the underlying mechanism, depending on the time horizon considered. Energy security shows an unambiguous positive relationship with CE development at both the correlation and the dynamic (error-correcting) level. Social security co-moves positively with the long-run equilibrium of the system, though this movement is driven by the adjustment of other components rather than by an independent correction of social security itself. Innovation and environmental security each present a striking divergence between horizons – both correlate strongly and positively with CE development in levels, yet both display a negative, persistent short-run dynamic response, consistent with structural adaptation to circular economy transformation carrying a short-run cost that coexists with a positive long-run trend. Financial security shows the weakest and least stable relationship, with a dynamic response that reverses sign within the observed horizon. No component exhibits statistically significant short-run Granger causality from CE development, indicating that where a relationship exists, it operates through long-run structural channels rather than short-term predictive dynamics.

These findings imply that a single, uniform policy approach to leveraging circular economy development for economic security is unlikely to be effective. Policies targeting energy and social security can reasonably expect gradual, equilibrium-consistent gains, while policies targeting innovation and environmental security should anticipate a short-run adjustment cost preceding any long-run benefit; the relationship with financial security remains too unstable, on current evidence, and is more likely to be mediated by broader macroeconomic adjustment processes than to emerge as a direct effect of circular economy development.

This study is subject to limitations inherent to a single-country annual time series of moderate length (24 observations), which constrains the precision of lag-order selection and dynamic stability assessment; one estimated root of the stationary VAR subsystem was found close to the unit circle, attributable to the near-unit-root persistence of innovation security. Future research should extend this empirical validation to additional circular-economy-leading economies and examine whether the differentiated pattern identified here generalizes across institutional contexts, including the transfer of these empirically established relationships to economies at an earlier stage of circular economy adoption.

Declaration on the use of artificial intelligence. During the preparation of this article, the author has used the AI assistant Claude (Anthropic, Claude Sonnet 5) to improve the linguistic quality and academic style of the manuscript, refine its structure, verify the consistency of econometric calculations and model specification, and support the presentation of the results. All analyses, interpretations, and conclusions are those of the author. All results produced using artificial intelligence have been reviewed by the author. The author bear full responsibility for the scientific validity, accuracy, and integrity of the content of this article.

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