Comparative Economic Research

Central and Eastern Europe

Volume 29 No. 3/2026

WYDAWNICTWO UNIWERSYTETU ŁÓDZKIEGO

WYDZIAŁ EKONOMICZNO-SOCJOLOGICZNY Uniwersytet Łódzki

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Łódź 2026

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COPE
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JM13708

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Printed directly from camera-ready materials provided to the Lodz University Press

Journal affiliated with the Faculty of Economics and Sociology
of the University of Lodz

Published by Lodz University Press
First Edition. W.12201.26.0.C
Printing sheets 28.0

ISSN 1508-2008
e-ISSN 2082-6737

Lodz University Press
90-237 Łódź, 34A Matejki St.
www.wydawnictwo.uni.lodz.pl
e-mail: ksiegarnia@uni.lodz.pl
tel. +48 42 635 55 77

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Comparative Economic Research. Central and Eastern Europe
Volume 29 Number 3, 2026
https://doi.org/10.18778/1508-2008.29.17

Bank-lending Channel, Monetary Policy, and Bank-level Heterogeneity: Contrasting Evidence from the Euro Area and Scandinavia

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Abstract

This paper investigates how bank-specific attributes influence the bank-lending channel across monetary policy cycles for commercial banks from the euro area and three Scandinavian countries (Denmark, Norway, Sweden) over the period 2004–2020, covering more than 3,200 institutions. Using fixed effects panel regressions on unconsolidated BankScope/Orbis data, we quantify the differential impact of changes in the monetary policy stance (including policy-rate increases) conditional on bank size, capitalisation, profitability and loan-loss provisioning. The results show that larger banks curb lending significantly less than their smaller peers, especially in Sweden and Norway; well-capitalised banks also cushion the contraction, whereas high provisioning amplifies it. The findings highlight the importance of tailoring macroprudential buffers to institutional structures and caution against a one-size-fits-all approach within the European Single Market. By contrasting regulatory and monetary regimes, the study contributes to the comparative literature on monetary transmission and offers comparative, ex-ante insights for authorities still navigating the post-pandemic tightening cycle.

Keywords: bank-lending channel, monetary policy, bank heterogeneity, euro area-Scandinavia comparison
JEL: C23, E52, E58, G21

Funding information: Faculty of Management, University of Warsaw, Warsaw, Poland.
Conflicts of interests: None.
Ethical considerations: The Author assures of no violations of publication ethics and takes full responsibility for the content of the publication.
Received: 22.09.2025. Verified: 20.10.2025. Accepted: 2.07.2026

Introduction

The post-2022 shift in monetary policy stance represents one of the most pronounced policy reversals in Europe in recent decades. Over this period, the European Central Bank (ECB) raised its deposit-facility rate by 375 basis points, while central banks in Scandinavia – specifically Sweden, Norway and Denmark – adjusted their monetary policy stances in response to the same inflationary and geopolitical shocks, albeit with important cross-country differences in the timing and intensity of rate changes. Although driven by broadly similar macroeconomic factors, the structural and institutional settings of banking sectors within these regions differ significantly.

The dataset concludes in 2020, prior to the onset of the latest rate increases; accordingly, it includes two historical subperiods (2006–2008 and 2017–2019) that are used as episodes of monetary normalisation or a less-accommodative stance, rather than as uniform tightening cycles across all jurisdictions. These periods provide a valuable empirical laboratory for analysing how institutional design conditions the lending channel. Importantly, these subperiods are not interpreted as synchronised tightening episodes across the euro area and Scandinavia. In particular, between 2017 and 2019, monetary policy in Sweden and Denmark remained highly accommodative, with policy rates at or below zero, while Norway experienced gradual normalisation. We, therefore, exploit within-country variation in the monetary stance and treat these subperiods as relative shifts in policy stances within each jurisdiction, rather than common tightening shocks across regions.

The 2022–2024 episode is used purely as contemporary motivation; therefore, the results should be interpreted as ex-ante lessons for the present cycle rather than an ex-post evaluation. The 2004–2020 window is predominantly accommodative; we, therefore, examine transmission across policy cycles using 2006–2008 and 2017–2019 as historical contrasts in the monetary stance. An additional driver of the post-2022 tightening was the unconventional pandemic-era expansion of money and fiscal support, which reshaped liquidity and inflation dynamics. References to the 2022–2024 cycle serve as contemporary motivation only.

Within the euro area, banks operate under a unified monetary framework administered by the ECB. Conversely, Scandinavian banking sectors face nationally distinct monetary policies, characterised by differences in policy rates and regulatory environments. Moreover, euro area banks predominantly rely on retail deposits, while Scandinavian banks significantly depend on wholesale funding, particularly through deep, liquid covered-bond markets. Additionally, the early and proactive adoption of macro-prudential measures, such as positive-neutral countercyclical capital buffers (CCyBs), in Scandinavia starkly contrasts with the relatively conservative and delayed implementation within the euro area.

This paper extends existing research by systematically examining how bank-specific attributes – such as size, capitalisation, profitability, and asset quality – mediate the bank-lending channel's response to episodes of monetary normalisation or a less-accommodative stance across these markedly different institutional frameworks. Utilising panel data covering 2004–2020 for 2,978 euro-area banks and 295 Scandinavian banks, this study aims to elucidate how bank characteristics can yield divergent lending behaviours depending on surrounding institutional and structural contexts.

The empirical findings underscore significant institutional effects on monetary transmission mechanisms. Large banks consistently demonstrate greater resilience to monetary shocks. However, the buffering role of capital adequacy appears effective only when regulators explicitly communicate the usability of capital buffers, a dynamic clearly evidenced in Denmark. Conversely, Swedish banks, which view capital buffers as rigid and non-negotiable, respond by precautionary hoarding, exacerbating the credit contraction. Profitability operates differently depending on the banking system's funding structure; in wholesale-funded systems, such as Norway, profitability mitigates contraction, whereas in euro-area banks reliant on deposit funding, profitability intensifies credit rationing. Moreover, asset quality implications diverge notably, conditioned by varying collateral valuation methodologies and provisioning practices across these distinct banking models.

The evidence presented challenges the effectiveness of uniform regulatory strategies, instead highlighting the importance of tailoring macro-prudential policies to institutional and structural specificities. Policymakers must acknowledge that interactions between bank-specific characteristics and broader institutional structures crucially affect monetary policy effectiveness.

This paper contrasts a unified monetary regime (the euro area) with national regimes (Denmark, Norway and Sweden) to test whether bank-level transmission depends on institutional context. The euro area embeds a common policy rate and shared market infrastructures, while these countries retain national policy tools and supervisory practices. Funding structures differ materially: the euro area is more deposit-funded on average, whereas Scandinavian systems feature a stronger wholesale and covered-bond bias. These contrasts shape the marginal cost of funding and the scope to reprice liabilities when policy shifts. Macroprudential buffer usability also diverges. In some Scandinavian jurisdictions, countercyclical and other buffers were signalled as usable under stress, whereas euro-area practice has at times been more conservative. We, therefore, hypothesise heterogeneous pass-through by bank size, capitalisation, profitability and asset quality, conditional on these institutional features, and structure the empirical design accordingly.

The paper is structured as follows. Section 2 presents the literature review underpinning the bank-lending channel and our research hypotheses. Section 3 details the data sources, the econometric methodology employed, and the descriptive statistics. In Section 4, we present the main empirical results, contrasting the findings for the euro area and individual Scandinavian countries. The paper concludes with Section 5, which summarises the findings, discusses the macro-prudential policy implications, and suggests directions for future research.

Literature Review

The conceptual foundations of the bank-lending channel were articulated by Bernanke and Blinder (1988), who emphasised that monetary policy affects real economic activity not only through interest rates but also by influencing banks' ability and willingness to extend credit. In their framework, contractionary open-market operations reduce reserves held by depository institutions, thereby limiting loan extension when bank credit cannot be perfectly replaced by other assets. This theoretical contribution subsequently inspired a broad empirical literature exploring the circumstances under which monetary policy actions propagate through banks' lending decisions.

Building on this theory, Kashyap and Stein (1995) exploit cross-sectional differences in bank size and balance-sheet liquidity to assess how monetary tightening propagates through loan supply. Their findings indicate that after a tightening of monetary policy, smaller banks, constrained by their dependence on core deposits, reduce lending substantially more than larger banks, which are typically better equipped to tap alternative funding sources. This evidence underscores that the strength of the bank-lending channel varies inversely with bank size and intensifies when institutions face greater liquidity constraints.

Kishan and Opiela (2000) extend the bank-lending channel literature by demonstrating that capital adequacy critically shapes banks' responses to monetary tightening. By analysing U.S. commercial banks sorted by Tier 1 capital ratios, they show that banks with lower capital ratios respond to policy rate hikes by sharply cutting back on lending, while institutions with stronger capital positions tend to preserve their credit extension capacity. This evidence emphasises that regulatory capital requirements and individual institutions' balance-sheet strength play a central role in amplifying monetary policy's effects via the lending channel.

Taken together, these foundational and early empirical works established that the efficacy of the bank-lending channel is not uniform across institutions but is critically mediated by bank-specific characteristics such as size, liquidity, and, crucially, capital adequacy, thereby setting the stage for more nuanced investigations into these micro-level determinants.

Subsequent research within European banking systems has validated and extended these findings. De Haan (2001) utilised bank-level panel data from the Netherlands to demonstrate that monetary tightening leads to disproportionately large contractions in unsecured lending at institutions whose capital ratios lie in the lowest quintile, indicating that thinner capital buffers amplify banks' sensitivity to policy shocks. Similarly, De Santis and Surico (2013) estimate panel regressions on bank loan growth across euro-area countries and find that cooperative banks in Germany and savings banks in Italy cut lending by significantly more than their commercial counterparts following policy tightenings – a pattern they link to these institutions' ownership forms, liquidity profiles, and localised market orientation. Altavilla, Canova, and Ciccarelli (2016) assemble a detailed monthly bank-level dataset for the euro area and document that banks in the bottom quartile of capital ratios or with elevated non-performing-loan shares reduce their lending rates – and therefore credit supply – far more in the wake of conventional rate hikes and targeted refinancing operations than do their better-capitalised peers, underscoring the centrality of balance-sheet strength in the lending channel. Collectively, these European investigations not only corroborated the earlier U.S. findings on the importance of factors like capital in the monetary transmission mechanism but also began to highlight how diverse institutional settings and bank ownership structures within developed economies could further modulate the bank-lending channel.

The role of profitability introduces additional complexity into the bank-lending channel literature. While not directly modelling lending behaviour, Caparusso, Lewrick, and Tarashev (2023) use a panel of global systemically important banks to show that banks projecting higher returns and maintaining larger discretionary capital cushions exhibit stronger market valuations and enjoy more flexibility relative to regulatory capital thresholds. Gambacorta and Marques-Ibanez (2011) presented evidence that banks with lower core capital ratios, heavier reliance on market funding, and larger shares of non-interest income

reduced lending more sharply during both policy tightening and the financial crisis, demonstrating that funding structures and income composition critically determine banks' responses to monetary shocks. Thus, the literature progressively painted a more intricate picture, revealing that beyond traditional balance sheet metrics, banks' profitability, reliance on market funding, and income diversification also significantly condition their lending response to monetary policy shifts, adding further layers of complexity.

Distinct institutional features of Scandinavian banking systems provide valuable comparative insights into the functioning of the bank-lending channel. Danmarks Nationalbank (Gundersen, Secher Hesselberg, and Hove 2011) underscored the structural importance of Denmark's covered bond market, noting that its deep liquidity and integration with mortgage financing distinguish it from traditional deposit-based systems. While not explicitly framed in terms of monetary transmission, the widespread use of covered bonds in Denmark suggests a potential redistribution of interest rate sensitivity away from banks and toward bond markets. Complementing this, Norges Bank (2023) emphasised the role of macroprudential tools – particularly the countercyclical capital buffer (CCyB) – in enhancing financial system resilience. By calibrating the CCyB in response to cyclical risks, Norwegian authorities aim to ensure that capital buffers remain usable during downturns, thereby moderating banks' procyclical lending responses to monetary policy shocks. Jordà, Schularick, and Taylor (2016) demonstrate, using over a century of disaggregated credit data for advanced economies, that real estate lending booms as early warning signs of financial instability, noting that credit expansions tied to property markets often precede deeper and longer-lasting economic recessions – underscoring the role of real-estate collateral in the monetary transmission process and in crisis amplification. These distinct institutional features and macroprudential approaches observed in Scandinavian economies, alongside broader historical findings on credit cycles, underscore that the bank-lending channel operates within, and is shaped by, specific national financial architectures and policy priorities, suggesting mechanisms that may differ systematically from those in other regions.

A growing literature examines the interplay between CCyBs and the transmission of monetary policy. Angelini, Neri, and Panetta (2014) employ a dynamic general-equilibrium model with a banking sector to show that coordinating countercyclical capital buffers with interest rate decisions enhances macroeconomic stability, especially when credit supply is disrupted by financial disturbances. Altunbas, Binici, and Gambacorta (2017) complement this with cross-country regressions linking macroprudential buffer movements to subsequent changes in banks' loan growth. They find that buffers built up during expansions tend to be drawn down in downturns – thereby smoothing credit cycles. The Basel Committee (Bank for International Settlements, 2017) and the European Systemic Risk Board (2020) both define CCyBs as capital add-ons that rise with systemic-risk indicators to restrain excessive credit expansion and to provide headroom for banks when stress hits. Empirical analyses reinforce the importance of design and timing: Jiménez et al. (2017), using Spain's dynamic-provisioning experiment, demonstrate that higher provisioning requirements during booms mitigate loan contractions in the subsequent crisis. Meanwhile, Acharya, Berger, and Roman (2018) document that the calibration and activation of capital buffers materially affect banks' risk-taking incentives and credit-supply responses under stress. This burgeoning body of research, therefore, converges on the view that while CCyBs can theoretically enhance

macroeconomic stability and smooth credit cycles, their practical effectiveness is contingent upon careful design, timely activation, and a clear understanding of their interaction with banks' underlying balance sheet strength and risk perceptions.

Gropp and Heider (2014) document that banks nearing their regulatory capital limits frequently avoid utilising these buffers due to concerns about reputational damage or heightened regulatory attention. As a result, institutions engage in precautionary capital hoarding, which can exacerbate credit contractions when monetary policy tightens. Haldane (2012) argues that only with clear, consistent, and credible communication from authorities regarding the conditions and implications of buffer use can banks gain confidence to draw on these reserves without fear of reputational or regulatory backlash. Survey evidence presented by Schoenmaker and Wierts (2016) confirms that jurisdictions where buffer-drawdown rules are transparently articulated see materially higher rates of actual buffer utilisation during downturns, indicating that perceived usability hinges on policymakers' articulation of drawdown frameworks. Consequently, the de facto utility of capital buffers in mitigating credit crunches appears significantly mediated by behavioural factors, such as the fear of stigma, and the credibility of regulatory communication, emphasising that the mere existence of buffers does not guarantee their use as intended shock absorbers.

Although the bank-lending channel has been extensively studied within individual jurisdictions (e.g. De Haan 2001; De Santis and Surico 2013; Altavilla, Canova, and Ciccarelli 2016), systematic cross-country comparisons remain relatively scarce. The predominance of single-region analyses constrains the generalizability of policy recommendations derived from such work. To fill this gap, the current study systematically contrasts euro-area and Scandinavian banking systems using harmonised bank-level data. This approach facilitates robust insights into how institutional differences mediate the impact of bank-specific characteristics, such as capital adequacy, on lending behaviour under monetary policy shifts.

We formulate the following hypotheses:

H1: Larger banks mitigate the contraction in lending after a rate hike.

H2: Higher capitalisation mitigates the contraction in jurisdictions where buffers are usable.

H3: Profitability mitigates the contraction in wholesale-funded systems.

H4: Higher impairments amplify the contraction, conditional on valuation practices.

Data and Econometric Methodology

The empirical work draws on an annual panel covering more than 3,200 banks over the 2004–2020 period. We splice BankScope (to 2015) with the Orbis/BankFocus files (2010–2020), hand-matching institutions where coding conventions differ. The merge yields a time-series long enough to observe both the macro backdrop (policy rates, inflation, unemployment, and GDP growth) and balance-sheet dynamics (total assets, loans, deposits, loan-loss provisions, and profitability, measured as return on assets (ROA)). After winsorising the extreme 1% tails of each bank-level variable and retaining banks with

at least six consecutive observations of loan growth, we obtain a clean panel containing over 2,700 banks suited to testing the bank-lending channel and its conditioning factors.

The identification does not rely on the assumption of homogeneous monetary tightening across regions. Instead, it exploits within-country variation in policy rates and heterogeneous transmission conditional on institutional settings and bank characteristics. Accordingly, the empirical results are interpreted as robust conditional correlations rather than structurally identified causal effects.

The analysis employs unconsolidated financial statements, aligning with methodological recommendations for isolating the bank-lending channel's transmission mechanisms (Kashyap and Stein 2000; Jiménez et al. 2012). Unconsolidated data provide a more precise representation of individual banks' standalone liquidity positions, capital adequacy, and lending capacity, which are critical for disentangling monetary policy effects on credit supply. By excluding subsidiary operations and intra-group transactions, this approach minimises confounding factors such as cross-subsidisation, regulatory arbitrage, and risk-sharing within banking conglomerates. In contrast, consolidated financial statements aggregate parent and subsidiary activities, thereby obfuscating the direct linkages between monetary policy shocks and core lending behaviours at the institutional level. This aggregation bias may attenuate empirical estimates of policy transmission efficacy, particularly in heterogeneous banking systems where parent-subsidiary interdependencies dilute granular insights (Borio, Gambacorta, and Hofmann 2015). Consequently, the use of unconsolidated data enhances the internal validity of the empirical analysis of monetary policy transmission at the bank level.

Although not directly included in the empirical model, selected indicators of market structure and financial depth are presented to provide context for cross-country differences in banking sector configurations and to outline directions for future research. For example, deposit-to-GDP ratios across the euro area reveal marked heterogeneity: from 385% in Luxembourg – reflecting its role as a financial hub (elevated ratios are also observed, for example, in Cyprus at 139% and Malta at 125%) – to just 40% in Latvia. Meanwhile, Scandinavian countries exhibit a narrower range (Denmark: 57%, Norway: 59%, Sweden: 62%), suggesting a degree of structural alignment despite differing macroeconomic and monetary frameworks. While not statistically analysed in this study, these disparities underscore the uneven intermediation capacity across jurisdictions. The observed convergence within the Scandinavian group, despite the absence of a unified monetary policy, points to the influence of region-specific regulatory frameworks or institutional complementarities that may support structural consistency across the region (e.g. Molyneux, Reghezza, and Xie 2019), warranting further investigation in future research.

Table 1. Characteristics of the banking sector

	Euro area	Denmark	Norway	Sweden
3-bank asset concentration	72%	82%	95%	93%
5-bank asset concentration	85%	90%	97%	96%
Bank deposits to GDP	93%	57%	59%	62%

Note: Average characteristics during the period covered by the analysis. 3-bank asset concentration – assets of the three largest commercial banks as a share of total commercial banking assets; 5-bank asset concentration – assets of the five largest banks as a share of total commercial banking assets; Bank deposits to GDP – total value of deposits in commercial banks and other financial institutions as a share of GDP.

Source: World Bank (Global Financial Development Database 2022).

Prior to examining the analysed characteristics, it is essential to assess the distinctions and commonalities among the studied markets from a data-driven perspective. The analysis first outlines changes in key policy rates within the euro area and Scandinavia, followed by an evaluation of the broader macroeconomic context, including indicators such as GDP growth and unemployment rates.

Chart 1. Interest rates, GDP growth and unemployment rate in the euro area and Scandinavian countries
Source: ECB, IMF.

Bank-level data includes key variables such as size (total assets), capitalisation (Tier 1 capital ratio), profitability (ROA), and asset quality (loan-loss provisions, LLP). Furthermore, these variables were standardised across the study sample to ensure comparability and facilitate the interpretation of the results. Each of these bank-specific variables is lagged by one year to mitigate potential endogeneity concerns.

The characteristics of the variables used in the model are outlined in the table below.

Table 2. Descriptive statistics of variables used in the model

Variable	EURO AREA		SCANDINAVIA		Denmark		Norway		Sweden	
	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev
d_loans_real	4.4	9.3	5.8	11.3	5.9	13.3	5.3	11.3	6.5	8.4
d_equity_real	6.5	9.1	7.1	11.5	6.7	11.8	7.3	12.1	7.3	10.0
d_cust_dep_real	5.0	15.8	6.5	10.8	7.0	12.9	6.3	10.9	6.3	7.8
gdpg	0.9	2.8	1.6	1.7	1.1	2.1	1.4	1.3	2.5	1.7

Variable	EURO AREA		SCANDINAVIA		Denmark		Norway		Sweden	
	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev
d_ir	−0.3	0.7	−0.3	0.9	−0.2	0.8	−0.2	1.1	−0.4	0.6
unempl	7.2	3.0	5.2	1.8	6.0	1.4	3.7	0.6	7.2	0.6
CR5	37.0	14.5	77.6	17.8	66.1	1.4	96.7	1.6	57.6	2.1
NIM	2.4	1.0	2.4	1.2	3.2	1.4	2.1	0.9	2.4	1.3
Size	13.5	1.6	13.3	1.7	13.3	1.9	13.3	1.4	13.4	2.1
CAP	17.4	6.2	19.2	4.8	18.6	5.2	18.6	3.4	21.2	5.9
ROA	0.3	0.6	0.9	0.8	0.7	1.1	0.8	0.5	1.1	0.7
LLP	0.5	1.0	0.5	1.0	1.2	1.6	0.2	0.4	0.2	0.5
N (banks)	2 505		268		70		120		78	
Obs	18 283		2 845		803		1 339		703	

Note: d_loans_real – real loan growth rate, calculated as the log difference of inflation-adjusted bank loans (percentage points); d_equity_real – real equity growth rate, computed analogously to d_loans_real using the logarithm of inflation-adjusted equity(percentage points); d_cust_dep_rea – real growth rate of consumer deposits, adjusted for inflation (percentage points); gdpg – annual GDP growth rate (percentage points); d_ir – change in the reference interest rate set by central banks (percentage points); unempl – unemployment rate (percentage points); Size – logarithm of total assets (in the table before standarisation); CAP – Tier 1 capital ratio, measuring core equity relative to risk-weighted assets (percentage points, in the table before standarisation); ROA – return on assets, defined as net income divided by total assets (percentage points, in the table before standarisation); LLP – loan-loss provisions ratio, calculated as loan-loss provisions divided by total assets (percentage points, in the table before standarisation).

Source: STATA; own calculations.

Due to the critical role of the d_loans_real variable in this analysis, its distribution across the studied countries is illustrated below. To address the structural diversity of the euro area, findings are reported separately for individual member states.

The baseline econometric specification used to capture the bank-lending channel's sensitivity to monetary policy, moderated by bank characteristics, is formulated as:

$$\begin{aligned}\Delta \mathrm{Loans}_{\mathrm{i,j,t}} = \alpha_1 + \alpha_2\, \Delta\, \mathrm{Loans}_{\mathrm{i,t-1}} + \alpha_3\, \Delta\, \mathrm{Equity}_{\mathrm{i,t}} + \alpha_4\, \Delta\, \mathrm{Dep}_{\mathrm{i,t}} \\ + \alpha_5\, \Delta\, \mathrm{ir}_{\mathrm{j,t-1}} + \alpha_6 \mathrm{gdpg}_{\mathrm{j,t-1}} + \alpha_7 \mathrm{unempl}_{\mathrm{j,t}} + \alpha_8 \mathrm{NIM}_{\mathrm{i,t}} \\ + \alpha_9 \mathrm{CR\,5}_{\mathrm{j,t}} + \beta_{\mathrm{k}} \mathrm{X}_{\mathrm{k,i,t}} + \gamma_{\mathrm{k}} (\mathrm{X}_{\mathrm{k,i,t}} \cdot \Delta \mathrm{ir}_{\mathrm{j,t-1}}) + \delta_{\mathrm{i}} + \mu_{\mathrm{t}} + \varepsilon_{\mathrm{i,j,t}},\end{aligned}$$

where, $\Delta \mathrm{Loans}_{i,t}$ represents the real growth rate of loans; $\Delta \mathrm{Equity}_{i,t}$ represents the real equity growth rate; $\Delta \mathrm{Dep}_{i,t}$ represents the real growth rate of consumer deposits; *NIM* (net interest margin) measures the difference between the interest income generated by banks and the amount of interest paid out to their lenders, divided by the amount of their average earning assets. $\Delta \mathrm{ir}_{j,t-1}$ captures the lagged annual changes in policy rates, while $X_{k,i,t}$ represents the set of *k* bank-specific characteristics (Size, CAP, ROA and LLP). The equation also includes the interaction term $X_{k,i,t} \cdot \Delta \mathrm{ir}_{j,t-1}$ between bank-specific characteristics and lagged annual changes in policy rates. Additionally, macroeconomic conditions ($\mathrm{gdpg}_{j,t-1}$, $\mathrm{unempl}_{j,t}$) are controlled to isolate policy effects precisely. CR5 denotes asset concentration, defined

as the assets of the five largest banks as a share of total commercial banking assets; δ_i denotes unobservable bank-specific effects; μ_t represents time fixed effects; and $\varepsilon_{i,j,t}$ represents white-noise errors. The indexes are marked: i – bank, j – country, and t – year.

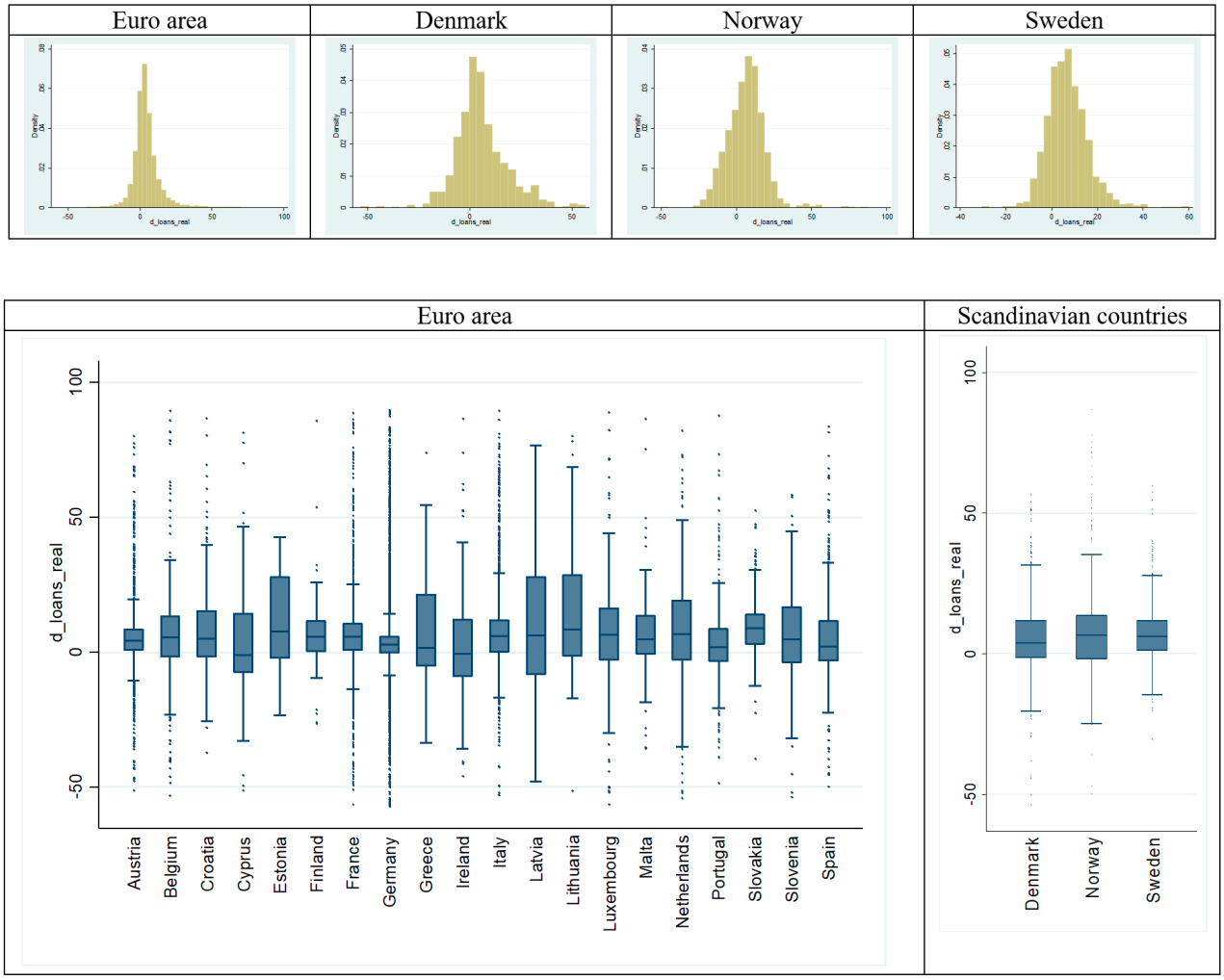

Chart 2. Real loan growth rate distribution
Source: STATA; own calculations.

The choice of a fixed effects (FE) panel estimator with a comprehensive set of control variables is a well-established and conservative approach in the empirical banking literature for isolating within-bank variation in lending behaviour (e.g., Kashyap and Stein 2000; Jiménez et al. 2012). While this specification does not claim to establish causality in a structural sense, it provides transparent and robust estimates of the conditional correlations central to our comparative research question. The FE framework effectively controls for time-invariant, unobserved bank heterogeneity, thereby mitigating a key source of omitted variable bias. Our rich set of controls, including lagged bank conditions and macroeconomic factors, further strengthens the credibility of the estimated associations between monetary policy, bank characteristics, and loan growth.

For the sake of reliable inference, we report both random effects (RE) and FE models in the appendix with standard errors clustered at the bank level (Table 4), FE regressions with Driscoll–Kraay standard errors (Table 5), and a dynamic specification estimated using system GMM (Table 6).

Bank-level clustering accounts for the unbalanced panel structure with varying numbers of banks across years and countries. As highlighted by Moody and Marvell (2020), clustering is essential in FE panel regressions to mitigate potential bias in standard errors and, consequently, unreliable inference regarding statistical significance. The Driscoll-Kraay estimator extends the standard FE framework by producing standard errors that are simultaneously robust to heteroskedasticity, serial correlation within entities, and cross-sectional dependence. This is particularly relevant in banking and macro-finance research, where common shocks – such as monetary policy decisions or regulatory changes – may affect all institutions in a given period, generating contemporaneous correlation across units. Coefficient estimates remain comparable to those obtained from standard FE regressions, while inference relies on a more robust variance-covariance structure.

In addition, we estimate a dynamic panel specification using the two-step system GMM estimator of Blundell and Bond (1998) with Windmeijer's (2005) finite-sample correction (Table 6) to address potential dynamic persistence and endogeneity concerns. Explanatory variables are instrumented using their own lagged values. The validity of the instrument set is assessed using the Hansen test of overidentifying restrictions. Results are interpreted cautiously and used as robustness checks rather than as primary causal estimates.

Empirical Results and Robustness Checks

It is important to frame the interpretation of the following results. This study is primarily exploratory and comparative in nature. Our aim is to document and contrast systematic patterns in how bank-level characteristics are associated with lending reactions to monetary policy across different institutional settings. The findings are, therefore, interpreted as robust conditional correlations that illuminate heterogeneous transmission channels, rather than as causal estimates. This comparative lens is valuable because it highlights where institutional context appears to matter most, providing a map for future research and more targeted policy analysis.

The econometric approach is rooted in a fixed effects panel model, chosen after comprehensive diagnostic testing, including Hausman specification tests favouring fixed effects over random effects models. The baseline FE estimation results are summarised in the table below, while supplementary specifications – including RE models and FE regressions with robust standard errors clustered at the bank level (utilising a fixed effects variance-covariance estimator, or FE-VCE) – are reported in the appendix (Table 4). To preserve clarity in the primary results, Scandinavian countries are aggregated and analysed as a regional subset exclusively in the supplementary appendix (Table 4, models 9–10). The models estimate the influence of bank-specific determinants (Size, CAP, ROA, LLP) on credit growth dynamics. However, the central empirical contribution lies in the statistically significant interaction effects between these bank-specific determinants and lagged changes in the policy rate (Δir_{t-1}), which reveal heterogeneous transmission channels contingent on institutional liquidity and capitalisation buffers. Because bank traits are z-scored, a one-standard-deviation increase in a specific trait changes the marginal effect of a 1 p.p. rate hike by the corresponding interaction coefficient; for example, in Sweden, $\gamma(\mathrm{Size}_t \cdot \Delta \mathrm{ir}_{t-1}) = 0.79$ implies materially smaller contractions for larger banks. Where coefficient signs diverge from standard priors, we avoid strong structural claims and treat such patterns as context-specific correlations. Modest

R^2 is expected with annual bank-level growth rates, where borrower demand and idiosyncratic shocks dominate; nevertheless, FE with rich controls still identifies average marginal effects. Alternative specifications and additional tables are provided in the appendix; figures are illustrative, and inference relies solely on the regression tables.

Table 3. Fixed effect model

VARIABLES	Euro area		Denmark		Norway		Sweden	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L.d_loans_real	0.053***	0.051***	0.037	0.030	−0.002	−0.002	0.014	−0.014
	(0.007)	(0.007)	(0.036)	(0.036)	(0.017)	(0.017)	(0.036)	(0.036)
d_equity_real	0.237***	0.237***	0.161***	0.161***	0.388***	0.373***	0.142***	0.158***
	(0.008)	(0.008)	(0.039)	(0.038)	(0.027)	(0.027)	(0.034)	(0.034)
d_cust_dep_real	0.132***	0.132***	0.320***	0.333***	0.511***	0.510***	0.429***	0.411***
	(0.004)	(0.004)	(0.030)	(0.031)	(0.028)	(0.027)	(0.040)	(0.040)
L.gdpg	0.052*	0.039	1.327***	1.383***	0.567***	0.598***	0.314*	0.307
	(0.031)	(0.031)	(0.490)	(0.499)	(0.191)	(0.189)	(0.190)	(0.190)
L.d_ir	−0.627***	−0.488***	−2.752**	−2.491*	0.223	−0.026	−2.472***	−3.500***
	(0.112)	(0.118)	(1.392)	(1.410)	(0.281)	(0.309)	(0.650)	(0.666)
Size	−0.875***	−0.675***	−2.266	−2.174	−3.543***	−3.777***	1.266	0.911
	(0.254)	(0.257)	(1.806)	(1.801)	(1.244)	(1.248)	(1.974)	(1.943)
CAP	−0.272***	−0.264***	−0.516***	−0.408***	−0.397***	−0.404***	−0.162*	−0.223**
	(0.022)	(0.022)	(0.110)	(0.114)	(0.102)	(0.102)	(0.091)	(0.095)
ROA	0.857***	0.703***	0.713	0.591	−1.416*	−1.346*	−1.838***	−1.603**
	(0.170)	(0.179)	(0.635)	(0.632)	(0.797)	(0.798)	(0.620)	(0.690)
LLP	−0.110	−0.072	−0.100	−0.487	−2.573***	−2.364***	0.039	−1.844
	(0.081)	(0.086)	(0.438)	(0.446)	(0.765)	(0.772)	(0.790)	(1.201)
Size_Ld_IR		0.416***		0.030		0.353**		0.793***
		(0.054)		(0.232)		(0.153)		(0.177)
CAP_Ld_IR		0.015		0.257***		0.003		−0.127*
		(0.015)		(0.088)		(0.060)		(0.069)
ROA_Ld_IR		−0.403**		−1.095*		0.144***		0.955
		(0.181)		(0.580)		(0.038)		(0.743)

VARIABLES	Euro area		Denmark		Norway		Sweden	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
LLP_Ld_IR		0.159		− 1.732***		0.597		− 2.809**
		(0.111)		(0.519)		(0.616)		(1.360)
unempl	− 1.070***	− 1.076***	− 3.100***	− 3.025***	1.048**	0.799*	− 1.880***	− 1.927***
	(0.041)	(0.042)	(0.486)	(0.486)	(0.462)	(0.466)	(0.621)	(0.628)
CR5	− 0.150***	− 0.154***	0.251	0.371	− 0.121	− 0.070	0.297*	0.301*
	(0.014)	(0.014)	(0.290)	(0.311)	(0.180)	(0.180)	(0.169)	(0.166)
NIM	1.322***	1.425***	1.289*	1.507**	2.801***	3.312***	1.510***	1.361***
	(0.163)	(0.165)	(0.699)	(0.698)	(0.746)	(0.748)	(0.438)	(0.438)
Constant	11.291***	11.332***	− 2.828	− 12.324	0.238	− 4.692	− 5.681	− 5.518
	(0.829)	(0.828)	(18.523)	(20.064)	(16.577)	(16.542)	(9.461)	(9.306)
Observations	18,165	18,165	800	800	1,339	1,339	703	703
No. of Banks	2,503	2,503	70	70	120	120	78	78
R-sq Within	0.260	0.263	0.459	0.472	0.691	0.700	0.356	0.389
R-sq Between	0.050	0.048	0.195	0.201	0.454	0.418	0.251	0.220
R-sq Overall	0.132	0.131	0.374	0.384	0.596	0.578	0.255	0.323

Note: Standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The variables Size, CAP, ROA, and LLP were standardised (z-score transformation) prior to model estimation to mitigate multicollinearity and facilitate coefficient interpretation. Interaction terms were constructed as the multiplication of each standardised variable and lagged policy rate changes (Δir_{t-1}), thereby isolating the moderating role of monetary policy shocks on bank-specific characteristics. This specification allows for testing heterogeneous monetary policy transmission across institutions, where the marginal effect of a rate change depends non-linearly on pre-existing liquidity (Size), capitalisation (CAP), profitability (ROA), net interest margin (NIM), risk provisioning (LLP) and concentration ratio (CR5). Standardisation ensures that interaction coefficients reflect effect sizes in standard deviation units, enhancing comparability across variables (Wooldridge 2010).

Source: STATA; own calculations.

The empirical findings indicate that larger banks generally exhibit greater resilience to policy-rate increases; however, this relationship is not uniform across countries. Interaction estimates show that bank size significantly mitigates the contraction in loan growth in Norway and the euro area, while the corresponding interaction in Sweden is positive but less stable across specifications. In the case of Denmark, the size interaction coefficient is small and statistically insignificant. This pattern suggests that institutional factors, rather than sheer scale, condition the usability of balance-sheet diversification during episodes of monetary normalisation or a less-accommodative stance. The models reported in the appendix confirm the distinctiveness of the Danish results. It should also be noted that the *Size* variable proved to be statistically insignificant in the Swedish specification – both in the baseline model and in robustness checks. This outcome contrasts with a substantial body of empirical research, including our own findings, which typically underscore

the importance of bank size in explaining variations in credit dynamics. We, therefore, interpret the Swedish result cautiously as context-specific.

Capital adequacy shows marked cross-country heterogeneity. Drawing down capital buffers significantly offsets the initial change in Denmark, but the interaction is insignificant in the euro area and Norway and turns weakly negative in Sweden. The *CAP* variable exerts a statistically significant influence on credit dynamics across all examined Scandinavian countries as well as in the euro area. This effect is consistently confirmed across all estimated models. These results qualify the earlier view that buffers are uniformly effective, highlighting instead that supervisory credibility and releasability are preconditions for buffer usability.

Profitability, measured by ROA, conditions the policy-lending relationship in the euro area once other characteristics are controlled for. In Denmark, higher profitability marginally also intensifies contraction, whereas in wholesale-funded Norway, it significantly mitigates the effect. The contrast underscores how funding structure mediates whether profits are deployed to protect market share or preserved through margin management.

Asset-quality interactions likewise diverge. Loan-loss provisioning amplifies the contraction in Sweden and Denmark but is neutral in Norway and in the euro area. The robustness checks presented in the appendix suggest that this conclusion should be interpreted with caution. Specifically, the VCE (bank cluster) models (Table 4) indicate that the interaction between *LLP* and the change in policy rate is statistically insignificant. Only in the case of Denmark is there evidence of a contractionary effect on credit growth (as shown in Table 5 in the regression with Driscoll-Kraay errors). Moreover, the direct impact of the *LLP* variable on credit growth proves to be insignificant in all countries except Norway (Table 4).

The observed cross-country differences in the significance of interactions between bank-specific determinants and lagged changes in the policy rate across the Scandinavian countries indicate that analysing the region as a single aggregate may yield limited insights. Consequently, the results presented in the appendix should be interpreted with appropriate caution. The estimated average effect for Scandinavia is primarily driven by the Danish, Norwegian, and Swedish subsamples. A nuanced understanding of the heterogeneity in national banking market characteristics is essential for accurately interpreting the effectiveness of the bank-lending channel.

The variables included in the model account for just 26% of the within-bank variance in lending in the euro area, compared to 70% in Norway and 47% in Denmark, highlighting the substantial role of institutional heterogeneity. All models presented in the main analysis are estimated using fixed effects. While alternative specifications reported in the appendix do not always yield identical coefficient magnitudes, the qualitative patterns are stable across estimation methods. To ensure comparability across subsamples, a consistent estimation technique was applied throughout the main analysis. The appendix reports both fixed effects and random effects estimates with bank-clustered standard errors, as well as models with Driscoll-Kraay standard errors and GMM estimation. Importantly, regardless of the estimation method, the core findings remain consistent. Beyond statistical significance, the magnitude of these moderating effects is economically meaningful.

Conclusion

This study provides a large-scale, comparative exploration of the bank-lending channel across the euro area and Scandinavia. By design, our analysis emphasises comparative patterns and institutional contrasts over causal identification. The core contribution lies in systematically demonstrating that the well-documented mediation of monetary transmission by bank-specific factors is not uniform, but is fundamentally reshaped by the surrounding monetary, funding, and regulatory environment. These empirical insights provide implications for regulatory frameworks and macro-prudential policies.

Firstly, the evident variation in capital buffer effectiveness underscores the importance of regulatory clarity regarding buffer usability. Policymakers should strive to establish clear, credible guidelines governing capital buffer deployment during economic downturns to prevent counterproductive precautionary behaviour, as observed in Sweden. The empirical results align with H1 in the euro area, Norway, and Sweden, whereas the effect is muted in Denmark; H2 is clearly supported only in Denmark; H3 shows a differentiated pattern – profitability mitigates contraction in Norway but is broadly neutral in the euro area; and H4 points to contractionary effects in Denmark and Sweden, with limited evidence in the euro area and Norway. Taken together, these outcomes indicate that the strength and even the direction of monetary pass-through depend on institutional architecture and cannot be generalised across jurisdictions. For Central and Eastern Europe and prospective euro adopters, the usability of buffers, funding structures, and valuation-sensitive provisioning should be made explicit in supervisory guidance and stress-testing.

Furthermore, the divergent role profitability plays in the euro area versus Scandinavian contexts emphasises the need for differentiated liquidity and funding regulations. Wholesale-funded systems might benefit from tailored liquidity management policies that recognise the stabilising role of profitability, while deposit-funded banks require vigilance against margin-protective credit rationing behaviours.

Lastly, asset-quality dynamics highlight the necessity of nuanced stress-testing and provisioning requirements reflective of specific collateral market characteristics. Two caveats merit emphasis. First, annual frequency masks intra-year balance-sheet adjustment; quarterly data (where available) could sharpen identification. Second, by terminating in 2020, the panel omits the large-scale liquidity facilities deployed during the pandemic-reopening phase. Consequently, the estimates provide a lower-bound on the shielding role of central-bank liquidity in the most recent cycle. Supervisors should incorporate region-specific asset-valuation practices into stress tests and prudential provisioning standards to better capture banks' risk exposure and response capacity during shifts in the monetary policy stance.

Overall, the evidence indicates that the effectiveness of the bank-lending channel varies across institutional frameworks within the euro area and Scandinavia. Bank characteristics such as size, capitalisation, profitability, and asset quality exert complex, context-dependent influences on lending responses to monetary policy stance. This underscores the limitations of uniform regulatory policies, advocating instead for tailored macro-prudential frameworks responsive to specific banking sector structures and institutional environments.

Future research should explore borrower-level data to further clarify demand-supply interactions, incorporate central bank liquidity interventions in monetary shock analyses, and investigate the increasingly pertinent issue of climate-related collateral risks within monetary policy transmission frameworks.

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Appendix

Table 4. Random effect model VCE (cluster Bank) and Fixed effect model VCE (cluster Bank)

VARIABLES	Euro area		Denmark		Norway		Sweden		Scandinavia	
	re vce (cluster Bank)	fe vce (cluster Bank)	re vce (cluster Bank)	fe vce (cluster Bank)	re vce (cluster Bank)	fe vce (cluster Bank)	re vce (cluster Bank)	fe vce (cluster Bank)	re vce (cluster Bank)	fe vce (cluster Bank)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
L.d_loans_real	0.207***	0.061***	0.108	0.028	0.044**	0.016	0.096**	− 0.002	0.106***	0.025
	(0.015)	(0.017)	(0.069)	(0.076)	(0.020)	(0.018)	(0.043)	(0.049)	(0.025)	(0.023)
d_equity_real	0.245***	0.243***	0.181***	0.193***	0.327***	0.369***	0.149***	0.171***	0.292***	0.302***
	(0.017)	(0.018)	(0.068)	(0.062)	(0.038)	(0.043)	(0.030)	(0.032)	(0.048)	(0.042)
d_cust_dep_real	0.124***	0.133***	0.327***	0.316***	0.558***	0.517***	0.473***	0.431***	0.472***	0.419***
	(0.020)	(0.018)	(0.084)	(0.078)	(0.039)	(0.042)	(0.037)	(0.041)	(0.069)	(0.061)
L.gdpg	0.092**	0.073*	0.611	0.829	1.078***	0.828***	0.295	0.405*	0.889***	0.661***
	(0.040)	(0.037)	(0.398)	(0.576)	(0.180)	(0.190)	(0.199)	(0.221)	(0.120)	(0.147)
L.d_ir	− 0.080	− 0.438***	− 1.019	− 1.043	− 0.627**	− 0.152	− 2.985***	− 3.298***	− 0.775***	− 1.244***
	(0.146)	(0.150)	(1.139)	(1.487)	(0.292)	(0.343)	(0.574)	(0.607)	(0.267)	(0.257)
Size	− 0.247***	− 0.840**	− 0.468***	− 3.796	− 0.885***	− 5.316***	− 0.047	− 0.906	− 0.401***	− 3.208**
	(0.060)	(0.381)	(0.151)	(2.911)	(0.164)	(1.312)	(0.261)	(2.854)	(0.119)	(1.489)
CAP	− 0.112***	− 0.344***	− 0.185	− 0.485*	− 0.180**	− 0.485***	− 0.044	− 0.294***	− 0.077	− 0.387***
	(0.018)	(0.042)	(0.145)	(0.278)	(0.085)	(0.125)	(0.052)	(0.099)	(0.063)	(0.101)

VARIABLES	Euro area		Denmark		Norway		Sweden		Scandinavia	
	re vce (cluster Bank)	fe vce (cluster Bank)	re vce (cluster Bank)	fe vce (cluster Bank)	re vce (cluster Bank)	fe vce (cluster Bank)	re vce (cluster Bank)	fe vce (cluster Bank)	re vce (cluster Bank)	fe vce (cluster Bank)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ROA	1.809***	1.539***	1.400**	0.913	0.798	− 0.195	− 0.233	− 0.947	0.052	0.018
	(0.265)	(0.305)	(0.608)	(0.651)	(0.502)	(1.022)	(0.440)	(0.693)	(0.053)	(0.051)
LLP	0.178	0.119	− 0.250	− 0.178	− 0.770	− 1.478	− 0.870	− 1.420	− 0.613	− 0.616
	(0.140)	(0.158)	(0.439)	(0.480)	(0.488)	(0.983)	(0.946)	(1.691)	(0.386)	(0.439)
Size_Ld_IR	0.381***	0.360***	0.045	0.113	0.363**	0.347**	0.494**	0.629***	0.162	0.227*
	(0.077)	(0.081)	(0.262)	(0.249)	(0.158)	(0.148)	(0.197)	(0.199)	(0.147)	(0.134)
CAP_Ld_IR	0.019	0.005	0.252*	0.250	0.049	0.024	− 0.068	− 0.111	0.055	0.059
	(0.023)	(0.025)	(0.152)	(0.163)	(0.052)	(0.057)	(0.085)	(0.098)	(0.091)	(0.089)
ROA_Ld_IR	0.080***	0.022	− 0.083	− 0.108	0.109*	0.128	0.143*	0.089	0.094*	0.095
	(0.029)	(0.031)	(0.076)	(0.109)	(0.065)	(0.078)	(0.085)	(0.104)	(0.051)	(0.066)
LLP_Ld_IR	0.256	0.228	− 1.009	− 1.387	0.905	0.713	− 2.010	− 2.961	0.133	0.286
	(0.191)	(0.205)	(0.726)	(1.028)	(0.932)	(1.048)	(2.165)	(2.652)	(0.468)	(0.539)
unempl	− 0.324***	− 1.063***	− 2.597***	− 2.590***	− 0.255	0.168	− 1.183**	− 1.517***	− 0.292**	− 2.361***
	(0.033)	(0.067)	(0.621)	(0.771)	(0.424)	(0.449)	(0.468)	(0.554)	(0.116)	(0.419)
Constant	3.350***	9.158***	16.054***	15.357***	− 1.450	− 2.591	8.529**	11.155***	− 0.157	11.340***
	(0.296)	(0.557)	(4.345)	(5.129)	(1.621)	(1.606)	(3.541)	(4.142)	(0.801)	(2.411)

VARIABLES	Euro area		Denmark		Norway		Sweden		Scandinavia	
	re vce (cluster Bank)	fe vce (cluster Bank)	re vce (cluster Bank)	fe vce (cluster Bank)	re vce (cluster Bank)	fe vce (cluster Bank)	re vce (cluster Bank)	fe vce (cluster Bank)	re vce (cluster Bank)	fe vce (cluster Bank)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Observations	18,248	18,248	797	797	1,339	1,339	702	702	2,838	2,838
No. of Banks	2,504	2,504	70	70	120	120	77	77	267	267
R-squared	0.213	0.251	0.449	0.463	0.687	0.694	0.363	0.378	0.496	0.525
Hausman Chi2		3316.32		8.25		65.21		60.39		88.74
p-value		0.00		0.8757		0.00		0.00		0.00

Note: Standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The Hausman test statistic is derived from the comparison between standard random effects and fixed effects models.

Source: STATA; own calculations.

Table 5. Panel Regression Results with Robust Standard Errors (Driscoll-Kraay SE)

VARIABLES	Euro Area		Denmark		Norway		Sweden		Scandinavia	
	(1)	(2)	(3)	(4)	(5)	(6)	(5)	(6)	(7)	(8)
L.d_loans_real	0.051**	0.029	0.030	− 0.046	− 0.002	0.001	− 0.014	0.004	0.018	− 0.014
	(0.023)	(0.019)	(0.071)	(0.063)	(0.021)	(0.027)	(0.029)	(0.044)	(0.023)	(0.029)
d_equity_real	0.237***	0.237***	0.161***	0.149***	0.373***	0.248***	0.158**	0.096	0.289***	0.251***
	(0.033)	(0.032)	(0.041)	(0.034)	(0.038)	(0.031)	(0.059)	(0.069)	(0.037)	(0.027)
d_cust_dep_real	0.132***	0.128***	0.333***	0.321***	0.510***	0.384***	0.411***	0.312**	0.429***	0.371***
	(0.013)	(0.012)	(0.102)	(0.089)	(0.052)	(0.063)	(0.092)	(0.115)	(0.062)	(0.068)
L.gdpg	0.039	0.410*	1.383	0.241	0.598*	0.505**	0.307	− 0.567**	0.664**	− 0.629
	(0.101)	(0.232)	(1.164)	(0.248)	(0.341)	(0.205)	(0.359)	(0.231)	(0.238)	(0.538)
L.d_ir	− 0.488	3.239	− 2.491	− 0.743	− 0.026	− 0.780*	− 3.500***	− 0.816	− 1.213**	− 1.337
	(0.406)	(2.692)	(3.107)	(1.005)	(0.472)	(0.415)	(0.840)	(1.425)	(0.497)	(1.247)
Size	− 0.675	1.440	− 2.174	5.448	− 3.777***	− 0.617	0.911	1.483	− 2.516***	2.216
	(0.798)	(1.428)	(2.761)	(3.270)	(1.239)	(1.451)	(1.863)	(2.008)	(0.813)	(1.612)
CAP	− 0.264***	− 0.207***	− 0.408***	0.026	− 0.404***	− 0.400***	− 0.223**	− 0.197**	− 0.330***	− 0.239***
	(0.048)	(0.045)	(0.095)	(0.135)	(0.125)	(0.130)	(0.089)	(0.074)	(0.095)	(0.064)
ROA	0.703	0.199	0.591	0.344	− 1.346	− 0.937	− 1.603*	− 0.433	− 0.291	− 0.324
	(0.429)	(0.399)	(1.082)	(0.514)	(0.966)	(0.874)	(0.796)	(1.174)	(0.507)	(0.543)

VARIABLES	Euro Area		Denmark		Norway		Sweden		Scandinavia	
	(1)	(2)	(3)	(4)	(5)	(6)	(5)	(6)	(7)	(8)
LLP	− 0.072	− 0.090	− 0.487	− 0.075	− 2.364***	− 1.476**	− 1.844*	− 2.043*	− 0.946*	− 0.352
	(0.230)	(0.272)	(0.802)	(0.508)	(0.693)	(0.658)	(0.932)	(0.975)	(0.493)	(0.392)
Size_Ld_IR	0.416***	0.441***	0.030	0.230	0.353*	0.461***	0.793***	0.640**	0.330	0.511**
	(0.070)	(0.076)	(0.221)	(0.220)	(0.182)	(0.155)	(0.213)	(0.230)	(0.234)	(0.223)
CAP_Ld_IR	0.015	0.030	0.257*	0.469***	0.003	− 0.002	− 0.127	− 0.051	0.041	0.108*
	(0.031)	(0.033)	(0.124)	(0.146)	(0.051)	(0.023)	(0.085)	(0.086)	(0.047)	(0.062)
ROA_Ld_IR	− 0.403	− 0.579	− 1.095**	− 2.220***	0.144*	0.107	0.955	− 0.387	0.921**	0.567
	(0.360)	(0.358)	(0.402)	(0.590)	(0.070)	(0.069)	(0.815)	(1.410)	(0.406)	(0.483)
LLP_Ld_IR	0.159	0.102	− 1.732***	− 1.177**	0.597	1.550***	− 2.809*	− 2.963	0.151	1.099**
	(0.179)	(0.162)	(0.396)	(0.449)	(0.388)	(0.405)	(1.381)	(1.724)	(0.396)	(0.425)
unempl	− 1.076***	− 0.996***	− 3.025***	− 2.752***	0.799	4.717***	− 1.927	0.195	− 2.365***	− 1.741**
	(0.160)	(0.156)	(0.970)	(0.618)	(0.810)	(0.913)	(1.294)	(1.593)	(0.743)	(0.738)
CR5	− 0.154***	0.183**	0.371	0.235**	− 0.070	− 0.208***	0.301	0.076	0.129	− 0.373
	(0.044)	(0.082)	(0.486)	(0.082)	(0.170)	(0.025)	(0.219)	(0.210)	(0.196)	(0.397)
NIM	1.425***	0.841*	1.507	0.807	3.312***	1.314	1.361***	− 0.870	0.786	− 0.417
	(0.397)	(0.450)	(1.483)	(0.880)	(1.068)	(1.093)	(0.416)	(0.586)	(0.782)	(0.779)
Constant	11.332***	8.101*	− 12.324	0.000	− 4.692	0.000	− 5.518	0.000	− 0.614	0.000
	(1.725)	(4.398)	(35.638)	(0.000)	(15.421)	(0.000)	(13.604)	(0.000)	(15.660)	(0.000)

VARIABLES	Euro Area		Denmark		Norway		Sweden		Scandinavia	
	(1)	(2)	(3)	(4)	(5)	(6)	(5)	(6)	(7)	(8)
Observations	18,165	18,165	800	800	1,339	1,339	703	703	2,842	2,842
No. of Banks	2,503	2,503	70	70	120	120	78	78	268	268
within R-squared	0.263	0.285	0.472	0.573	0.700	0.736	0.389	0.445	0.526	0.573
F	4 566	1 320	412.8	14 440	45 359	4 460	93.49	22 302	889.4	3 301
Year	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes

Note: Standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Source: STATA; own calculations.

Table 6. GMM Estimation Results (robust twostep)

VARIABLES	Euro Area	Denmark	Norway	Sweden	Scandinavia
	GMM lag(2 4)	GMM lag(2 2)	GMM lag(2 3)	GMM lag(2 4)	GMM lag(3 3)
	(1)	(2)	(3)	(4)	(6)
L.d_loans_real	0.005	− 0.080	− 0.019	− 0.086	0.009
	(0.135)	(0.142)	(0.026)	(0.099)	(0.030)
d_equity_real	− 0.034	0.070	0.233	0.227***	0.174**
	(0.109)	(0.170)	(0.156)	(0.078)	(0.082)
d_cust_dep_real	0.459***	0.155*	0.803***	0.482***	0.762***
	(0.138)	(0.080)	(0.161)	(0.089)	(0.076)
L.gdpg	− 0.017	3.607	0.749**	0.169	0.682***
	(0.118)	(2.197)	(0.331)	(0.212)	(0.261)
L.d_ir	− 0.529	− 6.064	− 0.343	− 3.952***	− 0.325
	(1.841)	(5.493)	(0.841)	(0.960)	(0.512)
Size	− 3.609	− 8.168	− 1.047	0.218	− 2.836
	(2.462)	(9.052)	(1.354)	(0.782)	(2.247)
CAP	1.994**	− 1.435***	− 0.039	0.380	− 0.323
	(0.879)	(0.534)	(0.363)	(0.391)	(0.294)
ROA	2.459	− 0.376	− 4.595*	− 4.790***	− 3.773***
	(4.499)	(2.737)	(2.668)	(1.668)	(1.156)
LLP	− 7.613***	− 1.149	− 16.383***	− 5.153	− 8.898***
	(1.824)	(2.049)	(3.895)	(3.939)	(1.469)
Size_Ld_IR	0.695	2.391	0.807**	1.322***	0.128
	(1.843)	(2.116)	(0.341)	(0.320)	(0.837)
CAP_Ld_IR	− 0.124	0.745	− 0.043	− 0.371**	0.050
	(0.816)	(0.479)	(0.213)	(0.173)	(0.201)
ROA_Ld_IR	1.228	− 0.736	− 0.028	− 0.426	4.047***
	(2.039)	(3.268)	(0.142)	(1.906)	(1.408)
LLP_Ld_IR	− 1.906	− 2.370	0.026	− 6.542	1.889*
	(2.321)	(2.268)	(2.755)	(4.193)	(1.098)

VARIABLES	Euro Area	Denmark	Norway	Sweden	Scandinavia
	GMM lag(2 4)	GMM lag(2 2)	GMM lag(2 3)	GMM lag(2 4)	GMM lag(3 3)
	(1)	(2)	(3)	(4)	(6)
unempl	0.312	− 2.179	1.412*	− 1.343	0.086
	(0.465)	(1.854)	(0.729)	(0.878)	(0.500)
CR5	− 0.010	0.830	− 0.364	0.486**	0.035
	(0.176)	(1.139)	(0.320)	(0.221)	(0.092)
NIM	9.353**	− 4.531	5.907**	2.665***	4.820***
	(3.779)	(4.913)	(2.863)	(0.971)	(1.453)
Constant	− 23.043**	− 29.628	14.882	− 23.472**	− 17.737*
	(9.640)	(84.570)	(28.716)	(11.090)	(10.063)
Observations	18,165	800	1,339	703	2,842
No. of Banks	2,503	70	120	78	268
No. of Instruments	49	45	76	61	61
AR(1) p-value	0.000	0.011	0.000	0.002	0.000
AR(2) p-value	0.741	0.400	0.371	0.477	0.168
AR(3) p-value	0.898	0.373	0.311	0.195	0.173
Hansen p-value	0.355	0.226	0.566	0.321	0.262

Note: Standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Source: STATA; own calculations.

Comparative Economic Research. Central and Eastern Europe
Volume 29 Number 3, 2026
https://doi.org/10.18778/1508-2008.29.18

Social Macroeconomic Imbalance Procedure (MIP) Indicators: Do They Matter?

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Abstract

The European Union's (EU's) Macroeconomic Imbalance Procedure (MIP) increasingly incorporates social indicators alongside traditional economic metrics, yet the empirical relationship between these dimensions remains underexplored. This study investigates whether social outcomes captured by the MIP scoreboard function as independent early-warning signals or merely reflect underlying macroeconomic conditions already monitored through non-social indicators. Analysing panel data for all 27 EU member states over 2001–2023, we employ LASSO regression for variable selection, two-stage fixed-effects estimation, and random forest analysis, validating results through Leave-One-Country-Out Cross-Validation. The findings reveal a fundamental dichotomy. Unemployment is robustly predicted by macro-financial variables, particularly non-performing loans and nominal unit labour costs, a result consistent across all three methods. In contrast, post-transfer poverty rates prove unpredictable from macroeconomic conditions regardless of model specification, suggesting that redistribution outcomes are decoupled from macro-financial variables and may be influenced by national tax-and-benefit systems not captured in the MIP scoreboard. Labour force participation similarly shows no significant association with any non-social indicator. We propose a dual-track reform: streamlining the MIP to focus on macroeconomic surveillance while establishing a parallel Social Convergence Framework for redistribution policy monitoring. Macroeconomic stability remains necessary for social progress across EU member states, but it does not account for poverty outcomes that appear linked to national social policies beyond the MIP's scope.

Keywords: Macroeconomic Imbalance Procedure, social indicators, unemployment, poverty, European Semester, EU economic governance, Social Convergence Framework

JEL: C51, E61, F45, I32, J64

Funding information: Wroclaw University of Economics and Business, Wroclaw, Poland
The percentage share of the Authors in the preparation of the work is: J.K. – 50.00%, K.B. – 50.00%.
Conflicts of interests: None.
Ethical considerations: The Authors assure of no violations of publication ethics and take full responsibility for the content of the publication.
Received: 15.11.2025. Verified: 8.01.2026. Accepted: 24.06.2026

Introduction

The global financial crisis of 2008 and the euro area sovereign debt crisis that followed exposed critical gaps in the European Union's (EU's) economic governance architecture. While fiscal rules had long been in place through the Stability and Growth Pact, no comparable mechanism existed for the early detection of broader macroeconomic risks such as excessive credit growth, unsustainable property price increases, or persistent current account deficits that could destabilise individual member states or the Economic and Monetary Union (EMU) as a whole. In response, the EU introduced the Macroeconomic Imbalance Procedure (MIP) in 2011 as part of the Six-Pack legislative package (European Parliament and Council of the European Union 2011). The MIP is designed to identify, prevent, and address potentially harmful macroeconomic imbalances within member states through a scoreboard of quantitative indicators. The scoreboard findings feed into the annual Alert Mechanism Report (AMR) and, where risks are identified, trigger In-Depth Reviews (IDRs) of individual countries. The MIP operates as a part of the European Semester, the Union's annual cycle of economic and fiscal policy coordination, in which the European Commission evaluates member states' budgetary plans, structural reforms, and macroeconomic developments.

The MIP scoreboard initially focused on "hard" macroeconomic indicators, e.g., current account balance, competitiveness, and debt measures (Franco and Zollino 2014:590–591), but over time, social indicators were also included. Since 2014, the scoreboard has incorporated certain labour market and poverty-related variables in recognition that macroeconomic imbalances often have social consequences. As of 2025, the MIP framework comprises 13 main indicators (of which two are explicitly social – unemployment rate and labour force participation rate, each with defined threshold values), and 23 auxiliary indicators (eight of which cover social domains without formal thresholds). These social MIP indicators track issues like unemployment (especially youth and long-term unemployment) and poverty (material deprivation, low work intensity households, and at-risk-of-poverty rates). However, despite their inclusion, social indicators have remained secondary in the MIP's implementation, which largely prioritises macroeconomic and financial stability concerns (Bricongne, Garcia, and Turrini 2019:3–4; Bacchini, Ruggeri Cannata, and Donà 2020:471; Roblek and Kejžar 2025).

In parallel to the evolution of the MIP, the EU proposed a Social Imbalances Procedure (SIP) in 2017 (Sabato, Vanhercke, and Guio 2022:22). While the SIP was intended to ensure that economic stability would not compromise social cohesion, it has since evolved into the Social Convergence Framework (SCF), officially integrated into the European Semester. The SCF utilises a two-stage analysis: the first identifies risks to upward social convergence via the Social Scoreboard in the Joint Employment Report (JER), while the second provides a deep-dive into specific Member States (e.g., ten countries in 2025). Although social indicators are now more rigorously monitored through this framework, they primarily inform policy coordination rather than triggering the strong enforcement or corrective actions characteristic of the MIP. Consequently, the JER remains the central instrument for assessing progress towards the European Pillar of Social Rights and formulating country-specific recommendations.

This context raises a critical governance question: do social MIP indicators contain incremental diagnostic information once the non-social scoreboard is taken into account, and how should they be interpreted within surveillance – as potential drivers, amplifiers, or primarily outcome indicators

of macro-financial developments? Importantly, informational overlap is not, by itself, a sufficient argument for removing an indicator from the MIP surveillance framework (scoreboard), especially when causal ordering is not identified. We therefore assess redundancy in a predictive/informational sense, asking whether social indicators add incremental diagnostic content beyond the non-social block. In governance terms, both weak linkages (suggesting structural decoupling and a distinct policy regime) and strong linkages (suggesting informational redundancy) may motivate relocating social indicators from the MIP scoreboard to a dedicated social monitoring pillar rather than "dropping" them altogether.

This article contributes to this debate by empirically evaluating the relationships between the social MIP variables and the non-social MIP variables. We assess whether deteriorations in social outcomes are systematically associated with developments in the non-social MIP indicators and whether the macro-financial block contains predictive content for social variables, without making causal claims about drivers versus outcomes.

Despite the importance of this issue for European social policy, to the best of our knowledge, no prior research has focused specifically on incremental diagnostic/predictive information of social MIP conditional on the non-social block. We address this gap by analysing a panel dataset covering all EU member states over the past two decades (2001–2023). Using several complementary quantitative methods, we test whether developments in twenty-six non-social MIP indicators contain incremental predictive content for changes in ten selected social indicators, without making causal claims. We thus treat the social indicators as dependent variables and examine their linkages to macroeconomic variables that the European Commission monitors for macroeconomic imbalance detection. In addition, we conduct random forest feature importance analyses to explore the relative significance of different macroeconomic variables in predicting social outcomes.

The novelty of this paper lies in its systematic empirical assessment of whether social indicators provide incremental information beyond the non-social scoreboard for imbalance surveillance, or whether they largely reflect the same underlying macro-financial information set while remaining relevant as welfare and distributional outcome measures.

Although the JER provides a rich analysis of the socio-employment situation, this article focuses exclusively on the MIP because it is the EU's primary mechanism for the surveillance and correction of imbalances, possessing potential enforcement mechanisms. This makes the role of social indicators within its framework a particularly critical issue from the perspective of economic governance.

In the remainder of the paper, we first review the relevant literature and theoretical expectations regarding macroeconomic and social imbalances. Next, we describe our data sources and methodology, which combines a LASSO-based variable selection approach, a two-stage selection procedure with univariate pre-screening and multivariate fixed-effects estimation, and random forest analysis, and we assess predictive performance using out-of-sample Leave-One-Country-Out Cross-Validation (LOCO-CV), a variant designed for grouped panel data. We then present the results of our empirical analysis and discuss their implications for EU policy. Finally, we conclude with reflections on whether the European Semester's current toolkit is adequate for addressing social imbalances or if reforms (such as a dedicated social monitoring procedure) are warranted.

Literature Review

Academic assessments of the MIP can be grouped into two broad strands (Domonkos et al. 2017:R35). The first strand examines the institutional and political dimensions of the MIP – its legal design, implementation, and the willingness of Member States to comply with recommendations. The second strand evaluates the empirical performance of the MIP's indicators, especially their ability to predict crises or signal vulnerabilities. Our study connects most closely with the second strand, as we are concerned with how indicators relate to one another and to socioeconomic outcomes.

Research on early warning systems has employed various definitions of "crisis". For example, some researchers define a crisis by a substantial drop in output (GDP) coupled with a surge in unemployment (Mishkin 2011:22). Others define crisis episodes when an indicator like the output gap or GDP growth deviates markedly from its trend (Harding and Pagan 2002; Domonkos et al. 2017:R36; Siranova and Radvanský 2018:341). Biegun and Karwowski (2020:15–17) introduced the concept of a "multidimensional crisis" based on several economic indicators, such as the decline in GDP, inflation, currency depreciation, stock market decline, and restrictions on cash withdrawals. This approach allowed them not only to identify crises but also to classify their severity.

Given these differing definitions, studies have sometimes reached divergent conclusions regarding which MIP scoreboard indicators are the most effective early warnings of trouble. The Joint Research Centre reviewed these papers and found varying results (Erhart, Becker, and Saisana 2018:28–29). Knedlik (2014:162–163) concluded that the current account, net international investment position, and nominal unit labour costs were the most useful predictors of a debt crisis. Boysen-Hogrefe et al. (2015:10–11) found that private sector credit flow, house prices, and private sector debt were the best indicators of future crises.

These findings align with earlier work on financial crises: Kaminsky (1999:16–17) identified several indicators of financial crises, including growth slowdown, loose monetary policy, overborrowing, bank runs, and balance of payments problems. Borio and Drehmann (2009:35–44) demonstrated that credit-to-GDP, equity, and property price gaps are able to detect the build-up of risks of upcoming banking distress. Sohn and Park (2016:195–198) found that credit growth is more informative in predicting banking crises than the credit-to-GDP gap, findings later confirmed by Geršl and Jašová (2018:27–30). Biegun and Karwowski (2020:20–22) identified five MIP variables that were statistically significant in predicting "multidimensional crises" for all EU countries: net international investment position, nominal unit labour cost index, house price index, private sector credit flow, and general government gross debt.

While significant research has focused on the economic and financial indicators in the MIP, the social indicators have received considerably less scholarly attention. Social variables like unemployment often appear in early warning studies as contributors to crises (e.g., rising joblessness as a symptom of an ongoing crisis) rather than as indicators to be explained. Among the early warning analyses, unemployment itself is sometimes treated as one potential alarm bell rather than as an outcome (Khalatur et al. 2022; Sinković, Zemla, and Zemla 2022). Siranova and Radvanský (2018) retrospectively evaluate the MIP indicators as early-warning tools for 17 Central and Eastern European economies covering 1991–2014, defining crises as years in which real GDP growth falls

more than one standard deviation below its five-year average and testing one-year-ahead signals within a two-year prediction window. Using a signalling framework with AUROC, absolute-utility (loss-function) metrics and noise-to-signal diagnostics, they show that labour-market "internal imbalance" indicators – closely aligned with today's social MIP items such as unemployment, youth and long-term unemployment, participation/activity, employment and NEET (neither in employment nor in education and training) – typically perform poorly at the Commission's official thresholds, often yielding AUROC values below 0.5 and negative absolute utility (i.e., no gain over a random benchmark). Optimising thresholds improves performance only modestly for most labour-market measures. However, the youth NEET rate emerges as a notable exception when calibrated around a 25% threshold, delivering positive utility and comparatively strong noise-to-signal properties. Overall, their evidence suggests that social/labour indicators generate substantial short-run "noise" as crisis predictors and are better interpreted as slow-moving structural imbalance measures to be assessed in-depth – an interpretation that motivates our broader test of whether social MIP indicators add independent information beyond non-social macro-financial indicators, or are largely redundant once the latter are accounted for.

Likewise, Boysen-Hogrefe et al. (2015) and Erhart, Becker, and Saisana (2018) point to a constrained role of the social (labour-market) dimension within the MIP when the framework is assessed through an early-warning lens. In a signalling-based evaluation of the scoreboard, unemployment – the key social item in earlier vintages – exhibits weak crisis-discrimination and low "usefulness" even after threshold optimisation, implying little actionable warning content for financial crises. Consistent with this evidence, broader assessments emphasise that the labour-market indicators later incorporated into the scoreboard (e.g., participation/activity, long-term unemployment, NEET) are mainly designed to inform the economic reading in in-depth reviews rather than to serve as hard procedural triggers, and that the scoreboard's overall performance as an EWS remains at best modest.

There is virtually no research explicitly examining whether the social imbalance indicators are systematically associated with other macroeconomic developments. This is an important gap, given that social outcomes might not move in lockstep with macroeconomic aggregates. For example, Europe's official poverty metrics are relative the at-risk-of-poverty rate measures the share of people below 60% of the median income. Strong GDP growth might not reduce this rate if income gains are unevenly distributed. Indeed, persistent inequality can mean that relative poverty and social exclusion remain high even during economic expansions.

The social MIP indicators, compared to measures used by organisations like the World Bank (2025), OECD (2025) and developed jointly by the Oxford Poverty and Human Development Initiative (OPHI) and the United Nations Development Programme (UNDP) (Oxford Poverty and Human Development Initiative 2025) are more focused on the causes of poverty, particularly unemployment in various dimensions. Additionally, there are measures of poverty or social exclusion, including after accounting for social transfers, expressed as the share of such individuals in the total population. While the World Bank's Multidimensional Poverty Index is better suited to significantly poorer countries than those in the European Union, both OECD Social Indicators and MIP social indicators assess social conditions but serve different purposes. The OECD indicators provide a broad assessment of well-being and inequality

across developed economies. In contrast, MIP social indicators are part of the EU's economic surveillance mechanism, focusing on social imbalances that may affect macroeconomic stability.

In summary, prior studies provide mixed evidence on which economic indicators are most important for anticipating crises, but they collectively highlight that macro-financial indicators (external balances, credit and asset prices) are critical. However, the "social imbalances" – issues like unemployment and poverty – have not been systematically studied in terms of their relationship with those macroeconomic indicators. Our analysis hence attempts to bridge this gap by investigating to what extent changes in social indicators can be statistically linked to the behaviour of macroeconomic imbalance indicators in the EU.

Data and Methodology

To empirically evaluate the prospective predictive power of macroeconomic imbalances on social outcomes, we employ a multi-methodological approach combining penalised regression, stepwise econometric selection, and non-parametric machine learning. This triangulation of methods allows us to mitigate the specific limitations of individual models, such as multicollinearity in standard regression or the lack of interpretability in "black box" algorithms. The analysis utilises a balanced panel of 27 EU Member States over the period 2001–2023 ($N = 27$, $T = 23$), comprising 621 country-year observations.

The panel's temporal dimension spans multiple economic cycles, including the global financial crisis, the European sovereign debt crisis, and the COVID-19 pandemic, thus providing substantial variation necessary for robust econometric identification. The dataset was constructed by integrating information from multiple authoritative sources, primarily Eurostat's Macroeconomic Imbalance Procedure database, supplemented with data from the European Commission's AMECO database and the European Central Bank's Statistical Data Warehouse, where necessary for completeness and cross-validation.

We focus on ten social indicators (dependent variables) and twenty-six non-social indicators (explanatory variables). The social indicators include the two headline (main) social MIP indicators as well as eight auxiliary social indicators without pre-set thresholds (Appendix 1). Together, these variables capture the major employment and social inclusion dimensions of the EU's social objectives (Appendix 2).

Variable Selection via LASSO

Given the high dimensionality of the potential regressor set relative to the time series length for individual countries, we first employ the Least Absolute Shrinkage and Selection Operator (LASSO) to identify the most relevant predictors. Following the seminal framework established by Tibshirani (1996), LASSO performs variable selection and regularisation to enhance the prediction accuracy and interpretability of the statistical model (Bickel, Ritov, and Tsybakov 2009; Carrico et al. 2015; Alshqaq and Abuzaid 2023).

The LASSO estimator minimises the residual sum of squares subject to the sum of the absolute value of the coefficients being less than a constant. Formally, for each social indicator y, we solve the following optimisation problem:

$$\widehat{\beta}_{\text{LASSO}} = \arg\min_{\beta} \left\{ \sum_{i=1}^{N} \sum_{t=1}^{T} \left(y_{\text{it}} - x_{\text{it}}^{'} \beta \right)^2 + \lambda \sum_{j=1}^{p} |\beta_j| \right\},$$

where x_{it} is the vector of macroeconomic predictors, β is the vector of coefficients, and $\lambda >= 0$ is the tuning parameter controlling the strength of the penalty. When λ is sufficiently large, some coefficients are forced to be exactly zero, effectively selecting a sparse subset of predictors. Prior to estimation, all variables are standardised to ensure the penalty is applied uniformly across regressors with different scales.

We run separate LASSO regressions for each of the ten social indicators, using the full set of 26 non-social indicators as candidate predictors. The regressions are panel-based in the sense that we include country and year fixed effects (via demeaning and year dummies) so that the LASSO picks up within-country, over-time associations. All variables are standardised to zero mean and unit variance prior to estimation to allow direct comparison of coefficient magnitudes. We select the LASSO tuning parameter through ten-fold cross-validation, minimising the mean squared error following Carrico et al. (2015) and Ghatari, Aminghafari, and Mohammadpour (2024). This yields a sparse model for each social indicator, including only the subset of non-social predictors with non-zero coefficients. We interpret a non-zero LASSO coefficient as evidence that the corresponding macro variable helps explain variation in the social indicator (after controlling for other variables). The sign and relative size of the coefficient *ß* indicate the direction and strength of the association. Following a heuristic common in applied LASSO studies (Tibshirani 1996; Schmidt and Makalic 2017), we treat any standardised coefficient larger than 0.25 in absolute value as a strong association.

Two-Stage Panel Data Approach

As a complementary method to LASSO, we implement a two-stage selection procedure designed to handle panel data heterogeneity explicitly.

Stage 1: Univariate Pre-screening. In the first stage, we conduct a univariate screening process to filter out irrelevant predictors. For each social indicator, we estimate bivariate panel regressions with fixed effects against each of the 26 macroeconomic variables. Variables that fail to meet a liberal significance threshold (p-value < 0.20) are discarded to reduce noise before the multivariate analysis.

Stage 2: Fixed-Effects Estimation. In the second stage, the surviving regressors are included in a multivariate Fixed Effects (FE) model. The specification is given by:

$$Y_{\text{it}} = \beta X_{\text{it}} + \mu_i + \varepsilon_{\text{it}},$$

where μ_i denotes the time-invariant country-specific effects, and ε_{it} is the idiosyncratic error term. Crucially, we employ the within-transformation (demeaning) to eliminate μ_i. Consequently, no global intercept (α) appears in the final equation, as it is absorbed by the fixed effects (or equals zero after centring the data). This approach ensures that our estimates are driven by within-country variations over time, consistent with the logic of the MIP surveillance, which monitors the evolution of imbalances. Inference is based on cluster-robust standard errors (HC1) to account for serial correlation and heteroscedasticity within panels (Cameron and Miller 2015).

This two-stage procedure ensures that we capture cases where a macro variable may be a good individual predictor but could be dominated by others when in the same model (Masakure 2015; Feng, Tong, and Chiu 2023). The outcome of this method is a set of conventional regression coefficients and *p*-values linking social and macro variables, which we can compare with the LASSO results.

Random Forest Analysis

To check the robustness of our linear specifications and capture potential non-linearities, we employ the Random Forest algorithm (Breiman 2001). Unlike linear regression, Random Forest builds an ensemble of decorrelated decision trees, providing a measure of variable importance without assuming a specific functional form (Strobl et al. 2007; Schauberger, Klug, and Berger 2024). For each social indicator, we grow a random forest using 500 regression trees, using all non-social indicators as inputs (with fixed country and time effects incorporated as additional features).

We report two key metrics of variable importance:

1. **%IncMSE (Increase in Mean Squared Error):** Measures the decrease in model accuracy when the values of a variable are randomly permuted. A higher value indicates that the variable is critical for prediction.

2. **IncNodePurity (Increase in Node Purity):** Measures the total decrease in node impurity (residual sum of squares) that results from splits over a variable, averaged over all trees.

To facilitate interpretation, we classify the variable importance into qualitative categories (Low, Moderate, High, Very High) based on the quartile distribution of these metrics across all predictors. This relative ranking avoids arbitrary thresholds and reflects the comparative predictive power of each macroeconomic variable.

This non-parametric approach serves as a validation tool: if the Random Forest identifies the same key predictors as LASSO and the FE model, our findings regarding the macroeconomic predictors of social imbalances are robust to model specification.

After applying all three methods, we compile the results to identify a set of robust associations between social indicators and macroeconomic variables. We consider a relationship robust if it appears in at least two of the approaches. The combination of approaches helps mitigate the limitations of any single method and provides a triangulation of evidence.

We must acknowledge the limitations of our approach regarding causal inference. First, while our models are specified with social indicators as dependent variables, this does not preclude the existence of reverse causality. For example, while a high level of non-performing loans (GNPL) might be a predictor for a rise in the unemployment rate (UR), it is also highly likely that high unemployment contributes to an increase in non-performing loans. Second, although the models control for time-invariant country-specific characteristics (fixed effects) and common shocks (time effects), the risk of omitted variable bias remains. Third, establishing definitive causal links would require different research strategies, such as instrumental variable (IV) models or dynamic panel models (e.g., GMM), which are beyond the scope of this predictive analysis but represent a promising avenue for future research.

We do not apply formal panel unit-root tests, as our primary objective is predictive assessment rather than cointegration analysis; the country and year fixed effects absorb time-invariant country heterogeneity and common shocks, while the out-of-sample validation framework provides a direct test of whether estimated relationships generalise beyond the estimation sample.

Results

The results of the **LASSO estimation** are presented in a matrix format: rows correspond to the 26 non-social macroeconomic variables (regressors), columns to the ten social variables (dependent variables), and cells contain the estimated LASSO coefficient for a given regressor in a given model.

To evaluate the results, a heuristic scale was applied to interpret the strength of LASSO coefficients, assuming that a strong association is present when the absolute value of beta exceeds 0.25. This threshold takes into account the typical distribution of LASSO coefficients, which are often small and rarely exceed 0.5 – unless the effect is genuinely substantial. In the analysed sample, 12 such cases were observed. Table 1 presents the results.

Table 1. Lasso demeaned results

Social MIP	Regressor	Beta
UR	NULC3	−0.27
UR	EMS3	0.26
UR	GNPL	0.33
LTUR	NULC3	−0.26
LTUR	GNPL	0.37
YUR	NULC3	−0.25
ER	GNPL	−0.33
YPEE	NULC3	−0.27
YPEE	RGDP	−0.39
PRPEST	NFCD	0.29
SMDP	HHCF1	−0.28
PLH	RGDP	−0.31

Source: own calculations.

In Table 2, we summarise the final multivariate fixed-effects estimates obtained from the two-stage procedure described above. For comparability across outcomes and predictors, the reported coefficients are fully standardised: within each final (equation-specific) estimation sample after listwise deletion of missing observations the dependent variable and all retained regressors are transformed into z-scores (mean zero, unit variance) prior to estimation. Hence, each $\widehat{\beta}_k$ can be interpreted as the change in a social MIP (in standard deviations) associated with a one-standard-deviation increase in the corresponding

non-social MIP, conditional on the other retained predictors and the country and year fixed effects. Statistical inference relies on country-clustered, HC1 cluster-robust standard errors.

To facilitate interpretation of practical relevance, we label the magnitude of each effect using the absolute value of the coefficient $\widehat{\beta}_k$: very weak (< 0.05), weak (0.05–0.20), moderate (0.20–0.50), strong (0.50–1.00), and very strong (≥ 1.00). The cut-offs at 0.20 and 0.50 are used as heuristic reference points consistent with widely cited "small/medium/large" conventions for unit-free effect sizes in the behavioural and social sciences (Cohen 1988:25–27 for d; 79–80 for r), while recognising Cohen's explicit caution that such conventions are context-dependent and should be treated only as a frame of reference when no better substantive calibration is available. Accordingly, these magnitude labels complement rather than replace formal inference. In Table 2, we highlight coefficients that are both non-trivial in magnitude ($|\widehat{\beta}_k| > 0.20$) and statistically distinguishable from zero at a chosen level ($p < 0.10$), enabling a concise comparison of non-social MIPs that appear most relevant for explaining standardised social outcomes.

Table 2. Final results from the two-stage pre-screening and multi-variate fixed effects

Social MIP	Regressor	Coefficient	Strength	*p*-value
UR	NULC3	− 0.21	moderate	0.002 292
UR	GDERD	− 0.27	moderate	0.047 313
UR	GNPL	0.27	moderate	0.000 004
LTUR	NIIPE	− 0.29	moderate	0.061 414
LTUR	GNPL	0.26	moderate	0.000 062
YUR	NULC3	− 0.21	moderate	0.00 772
YUR	GGSD	− 0.60	strong	0.059 145
YUR	GDERD	− 0.29	moderate	0.047 125
ER	HHDGDP	− 0.36	moderate	0.098 224
ER	HHDGDI	0.51	strong	0.049 037
YPEE	NIIPE	− 0.25	moderate	0.026 093
PRPE	HHDGDP	0.48	moderate	0.034 711
PRPE	HHDGDI	− 0.56	strong	0.016 039
PRPEST	NIIPE	− 0.32	moderate	0.00 712
PRPEST	RGDP	− 0.43	moderate	0.072 673
PLH	HHDGDP	0.73	strong	0.040 653
PLH	RGDP	− 0.93	strong	0.054 583
PLH	HHDGDI	− 0.69	strong	0.008 639

Source: own calculations.

For eight social MIPs, at least one non-social variable was found to be significantly associated with changes in the corresponding social outcome. In our analysis, the fully standardised coefficients allow for a direct comparison of effect sizes across different non-social MIPs. For example, for the unemployment rate (UR), the non-social variable gross non-performing loans of domestic and foreign entities as a percentage of gross loans (GNPL) exhibits a moderate association, with a standardised coefficient of 0.27. This implies that, holding other factors constant, a one-standard-deviation increase in GNPL is associated with a 0.27 standard deviation increase in UR.

Overall, these findings indicate that a small subset of macro-financial indicators displays non-trivial predictive associations with several social indicators within our standardised panel framework. This full standardisation improves comparability and highlights the practical relevance of the selected predictors, providing insight into informational linkages between non-social and social MIP indicators.

The **random forest results** produced a table containing all social MIP variables, all regressors (the explanatory variables whose importance was assessed, including both non-social indicators and the factors "country" and "year"), and two measures: *IncMSE* and *IncNodePurity*. In both cases, higher values signify a stronger predictive contribution of the regressor and thus reflect greater overall importance of that regressor.

There are no universal, fixed thresholds for *IncMSE* or *IncNodePurity*, because their absolute values depend on the underlying data and the specific model. In practice, these values are compared relative to each other within the same model. A common approach is to examine the distribution of importance values across predictors and then define custom thresholds. We classified the variables as follows:

- very high importance: predictors with values above the 75th percentile,
- high importance: predictors between the 50th and 75th percentiles,
- medium importance: predictors between the 25th and 50th percentiles,
- low importance: predictors below the 25th percentile.

Although these cut-offs are arbitrary, they enable a meaningful relative ranking of the predictors. Table 3 includes only those rows where *IncMSE* values were classified as "very high importance" and *IncNodePurity* values as either "high" or "very high importance". This selection reflects the fact that while *IncNodePurity* provides an additional perspective, primary emphasis should be placed on *IncMSE* when ranking predictors, as it offers a more robust measure of variable importance in the presence of correlated inputs.

Table 3. Random forest variable importance for social MIP indicators

Social MIP	Regressor	*IncMSE*	*IncMSE* cat.	*IncNodePurity*	*IncNodePurity* cat.
UR	NULC3	10.99	Very high	159.66	High
UR	GGSD	10.88	Very high	283.24	Very high
UR	HHCF1	10.68	Very high	344.01	Very high
UR	HPIN	13.03	Very high	134.75	High

Social MIP	Regressor	*IncMSE*	*IncMSE* cat.	*IncNodePurity*	*IncNodePurity* cat.
UR	NIIPE	10.50	Very high	114.03	High
UR	GNPL	10.69	Very high	194.60	Very high
UR	BP	15.44	Very high	519.23	Very high
LTUR	NIIP	13.08	Very high	123.31	High
LTUR	GNPL	14.22	Very high	159.37	High
LTUR	BP	18.21	Very high	380.64	Very high
YUR	NIIP	10.72	Very high	770.67	Very high
YUR	GGSD	14.13	Very high	2336.42	Very high
YUR	HHCF1	11.34	Very high	1190.25	Very high
YUR	HPIN	10.91	Very high	581.47	Very high
YUR	NIIPE	12.72	Very high	808.84	Very high
YUR	RGDP	11.39	Very high	348.21	Very high
YUR	BP	16.34	Very high	2918.54	Very high
ER	NULC3	11.28	Very high	173.12	High
ER	GGSD	14.06	Very high	620.31	Very high
ER	HHDGDP	10.56	Very high	137.71	High
ER	HPIN	10.86	Very high	228.10	Very high
ER	NIIPE	11.11	Very high	130.43	High
ER	RGDP	11.50	Very high	281.20	Very high
ER	GDERD	10.33	Very high	271.83	Very high
ER	GNPL	20.34	Very high	1209.07	Very high
ER	BP	15.43	Very high	1032.14	Very high
YPEE	CAB3	13.06	Very high	239.87	Very high
YPEE	NIIP	14.22	Very high	346.92	Very high
YPEE	HPIN	11.71	Very high	180.46	High
YPEE	RGDP	13.42	Very high	305.26	Very high
YPEE	HHDGDI	11.80	Very high	100.36	High
YPEE	GNPL	10.74	Very high	492.87	Very high
YPEE	BP	13.70	Very high	443.35	Very high
PRPE	HHDGDP	11.18	Very high	756.16	Very high

Social MIP	Regressor	*IncMSE*	*IncMSE* cat.	*IncNodePurity*	*IncNodePurity* cat.
PRPE	NFCD	11.88	Very high	153.98	High
PRPE	HHCF1	10.49	Very high	197.96	Very high
PRPE	RGDP	16.08	Very high	1490.70	Very high
PRPE	GDERD	13.50	Very high	682.84	Very high
PRPE	BP	15.78	Very high	450.91	Very high
PRPEST	GGSD	13.89	Very high	158.99	High
PRPEST	HHDGDP	10.73	Very high	118.30	High
PRPEST	RGDP	10.71	Very high	194.75	Very high
PRPEST	GDERD	15.96	Very high	411.45	Very high
PRPEST	BP	12.39	Very high	118.29	High
SMDP	HHDGDP	11.47	Very high	1080.58	Very high
SMDP	RGDP	15.82	Very high	2390.70	Very high
SMDP	GNPL	10.50	Very high	496.18	Very high
PLH	NULC3	16.60	Very high	278.06	Very high
PLH	NFCD	12.49	Very high	108.95	High
PLH	HHCF1	12.43	Very high	164.32	High
PLH	BP	10.35	Very high	74.15	High

Source: own calculations.

Although all three methods applied can be classified under the umbrella of multiple regression analysis and variable selection, they nonetheless represent distinct approaches to identifying which social MIP variables may be considered "redundant" in the sense that they exhibit significant associations with non-social MIP indicators. The results from the analyses reveal that most social MIP indicators have at least one significant association with a macroeconomic variable. Table 4 presents the results indicating which social MIP variables are linked to non-social MIP variables, based on the application of three methods: LASSO, stepwise regression procedure, and random forest. For a given non-social MIP variable to be included in the table, it had to be identified by at least two of the three methods.

Eight of the ten social indicators examined exhibit a clear relationship with one or more non-social MIP indicators. For the labour force participation rate (LFPR3), none of the methods identified such a relationship. In the case of the rate of severely materially deprived people (SMDP), potential associations with specific non-social variables were indicated by only one of the methods in a few instances.

Table 4. A summary of the findings on the relationships between social and non-social dimensions of the MIP

Method	Multiple Regression Analysis and Variable Selection		
	LASSO	Two-stage selection	Forest
Social MIP	Non-social MIP		
UR	GNPL (+)	GNPL (+)	GNPL
UR	NULC3 (–)	NULC3 (–)	NULC3
LFPR3			
LTUR	GNPL (+)	GNPL (+)	GNPL
YUR	NULC3 (–)	NULC3 (–)	
YUR		GGSD (–)	GGSD
ER	GNPL (–)		GNPL
ER		HHDGDP (–)	HHDGDP
YPEE	RGDP (–)		RGDP
PRPE		HHDGDP (+)	HHDGDP
PRPEST		RGDP (–)	RGDP
SMDP			
PLH	RGDP (–)	RGDP (–)	

Source: own calculations.

Notably, the **unemployment rate (UR)** is strongly linked to two macroeconomic indicators: higher nominal unit labour cost growth (NULC3) is associated with a lower UR (suggesting that wage growth tends to coincide with falling unemployment in an economic upswing), whereas higher non-performing loan levels (GNPL) are associated with a higher UR (consistent with financial stress leading to job losses). These relationships were the most consistently identified linkage across methods (flagged by LASSO, two-stage selection, and random forest alike).

Similarly, for the **long-term unemployment rate (LTUR)**, the share of gross non-performing loans (GNPL) in the banking sector proves to be a significant positive predictor: an increase in the proportion of non-performing loans is associated with a rise in long-term unemployment. This observation is consistent with theoretical expectations, as banking sector distress typically coincides with economic downturns that extend the duration of unemployment spells. The causality may also operate in the opposite direction: elevated unemployment can undermine debt servicing capacity, particularly among first-time borrowers with limited income stability.

Conversely, a higher gross non-performing loans ratio (GNPL) is associated with a lower **employment rate (ER)** defined as the share of working-age adults in employment reinforcing the notion that financial

crises and weak credit conditions are closely linked to labour market fragility. This relationship is supported by the results of both the LASSO and random forest methods.

A similar, and as in the previous case less robust pattern is found for **youth unemployment (YUR)**, which, like overall unemployment, correlates negatively with unit labour cost growth (NULC3) and general government gross debt as a percentage of GDP (GGSD), the latter relationship being supported by the random forest method.

Turning to poverty and social exclusion indicators, we find that overall economic growth plays a key role in improving several outcomes. In particular, a rise in real GDP per capita in EUR (RGDP) is strongly associated with subsequent reductions in the **share of youth not in employment, education or training (YPEE**), the **people at risk of poverty after social transfers (PRPEST)**, and the **very low work intensity rate (PLH)** all three of these social indicators decline when real incomes grow. Quantitatively, RGDP per capita was among the top predictors for those variables in the LASSO and two-stage selection models, indicating that a stronger economy leads to fewer young people disengaged from work or education and fewer households in (relative) poverty or joblessness. However, it is noteworthy that the indicator **people at risk of poverty or social exclusion (PRPE)** a broader composite measure did not exhibit a significant association with real GDP growth, but rather with household debt, including non-profit institutions serving households, consolidated; % of GDP). This suggests that general economic growth alone may not reduce relative poverty or social exclusion rates, possibly because the gains from growth are not evenly distributed.

Two social indicators stand out as not well-explained by the macro variables. The **labour force participation rate, as a percentage of the population aged 15–64 (LFPR3)**, measured as a three-year change, had no predictors among the 26 macro indicators. This implies that fluctuations in participation (the proportion of people active in the labour market) are associated with factors other than the monitored macroeconomic imbalances for example, demographic changes, education enrolment, migration, or policy reforms affecting retirement and childcare, which are not captured by the MIP scoreboard. Similarly, the **severely materially deprived people (SMDP; % of total population)** showed no consistent links to macroeconomic indicators. This indicator, which reflects extreme hardship, may be more influenced by social safety nets, targeted aid, and other social policies that mitigate deprivation independently of the economic cycle.

Out-of-Sample Prediction Results

To rigorously assess whether macroeconomic variables genuinely contain predictive information about social indicators rather than merely fitting in-sample noise we complement our estimation with out-of-sample prediction tests (Hastie, Tibshirani, and Friedman 2009). While in-sample metrics establish statistical associations, out-of-sample validation tests whether these patterns generalise across different national contexts.

We implement **Leave-One-Country-Out Cross-Validation (LOCO-CV)**, a variant of cross-validation specifically designed for panel data with grouped observations (Arlot and Celisse 2010). The procedure iterates through all $N = 27$ Member States; in each iteration, we:

1. Exclude all observations belonging to country *i* (the test set).
2. Train the models (LASSO and random forest) on the remaining *N* – 1 countries (the training set).
3. Predict the social indicator values for the held-out country *i*.

This approach ensures that the model never "sees" data from the target country during training, mimicking a true forecasting scenario where policy decisions must be made for a specific member state based on general EU-wide regularities.

We report the out-of-sample coefficient of determination R^2_{oos} as the primary performance metric:

$$R^2_{\text{OOS}} = 1 - \frac{\sum \left(y_{\text{it}} - \hat{y}_{\text{it}}\right)^2}{\sum \left(y_{\text{it}} - \overline{y}_{\text{train}}\right)^2},$$

where y_{it} denotes the observed value of the social indicator for country *i* at time *t*, $\hat{y}_{it}$ is the model's prediction, and $\bar{y}_{train}$ represents the mean of the observed values in the test set.

Table 5 presents the out-of-sample predictive performance, offering a rigorous test of whether macro-financial variables contain predictive information for social outcomes across different national contexts. The results reveal a striking dichotomy between indicators that are well-predicted by the macro-financial block and those that show weak or no links to it.

Table 5. Out-of-sample predictive performance

Social MIP	LASSO R2	RF R2	LASSO RMSE
UR	0.346	0.430	3.41
LTUR	0.439	0.576	2.19
YUR	0.329	0.447	7.91
ER	– 0.453	0.438	7.43
LFPR3	– 0.140	0.122	1.45
SMDP	0.297	0.697	5.85
PRPE	0.264	0.489	5.52
PRPEST	– 0.655	0.045	4.93
YPEE	0.494	0.307	3.43
PLH	0.133	0.149	2.96

Source: own calculations.

First, labour market exclusion is moderately predictable, but often requires non-linear modelling. The Random Forest model achieves substantial predictive power for Long-term Unemployment (R^2 = 0.58) and Youth Unemployment (R^2 = 0.45). Interestingly, for the Employment Rate (ER), the linear LASSO model fails completely (R^2 = –0.45), while the non-linear random forest recovers predictive

power (R^2 = 0.44). This suggests that while employment is linked to macro-fundamentals, the relationship is complex and may not be captured by simple threshold-based monitoring.

Second, and most critically for the policy debate, we observe a fundamental decoupling of poverty outcomes. While Severe Material Deprivation (SMDP) which is closely tied to GDP levels is highly predictable (R^2 = 0.70 in RF), the At-risk-of-poverty rate after social transfers (PRPEST) is virtually unpredictable from macroeconomic variables. The Random Forest R^2 for PRPEST is near zero (0.045), and LASSO performs worse than a random guess (–0.655).

This result indicates that macroeconomic conditions are associated with pre-transfer deprivation, whereas post-transfer poverty outcomes show limited predictive links with the macro-financial variables monitored by the MIP scoreboard in our modelling framework. This pattern suggests that post-transfer poverty may be influenced by country-specific tax-and-benefit institutions that are not proxied by the MIP's macro-financial indicators.

Discussion and Conclusion

This study examined the incremental diagnostic content of social indicators within the EU's Macroeconomic Imbalance Procedure scoreboard. Three principal findings emerge from our LASSO, two-stage selection, and random forest analyses. First, social indicators, particularly unemployment and poverty measures, tend to co-move with the non-social macro-financial scoreboard. Our models suggest that variables such as gross non-performing loans, nominal unit labour costs, real GDP per capita, and household debt are associated with a notable share of variation in employment and deprivation metrics, though the strength of these relationships varies across specifications. Second, we find marked heterogeneity across social indicators. While eight of the ten social outcomes exhibit robust associations with at least one macro-financial variable, the labour force participation rate shows no such linkages, and severe material deprivation displays distinct non-linear dynamics linked predominantly to income levels. This heterogeneity suggests that not all social outcomes respond uniformly to macro-financial developments. Third, our out-of-sample predictive exercises reveal that macro-financial variables explain a substantial share of variation in most labour market indicators, with random forest models achieving R^2 values between 0.43 and 0.58 for unemployment measures. However, predictive performance varies markedly: while severe material deprivation is highly predictable from macroeconomic conditions (RF R^2 = 0.7), the at-risk-of-poverty rate after social transfers remains virtually unpredictable (RF R^2 = 0.05). This pattern suggests that post-transfer poverty is only weakly linked to the macro-financial information set captured by the MIP scoreboard and may be influenced by country-specific tax-and-benefit institutions not proxied by these variables.

Our results suggest that most social indicators co-move with the macro-financial information set captured by the non-social scoreboard, with limited incremental predictive information beyond this non-social block in our modelling framework. The unemployment rate, for instance, is linked to gross non-performing loans and nominal unit labour cost growth, relationships consistently identified across all three methods. When unemployment or poverty thresholds are breached, this typically occurs after more fundamental economic imbalances have accumulated. This temporal hierarchy aligns with established research on business cycle dynamics. Cerra, Fatás, and Saxena

(2023) demonstrate that negative output shocks generate persistent labour market hysteresis, with unemployment recovering significantly slower than GDP. Bluedorn and Leigh (2019) corroborate this asymmetry, finding that labour force participation often fails to revert to pre-crisis levels for years following economic shocks. Similarly, the World Bank (2022) documents that poverty rates spike rapidly during downturns but decline sluggishly during expansions. Our results provide EU-specific evidence consistent with these broader patterns.

The findings also resonate with earlier evaluations of MIP scoreboard performance. Siranova and Radvanský (2018) show that labour-market indicators typically perform poorly as crisis predictors at official thresholds, often yielding AUROC values below 0.5. Boysen-Hogrefe et al. (2015) similarly find that unemployment exhibits weak crisis-discrimination even after threshold optimisation. Our results extend these insights by demonstrating that the informational content of social indicators is largely absorbed by macro-financial variables once both are considered jointly. However, our analysis reveals important nuances absent from earlier studies. The striking contrast between highly predictable severe material deprivation and virtually unpredictable post-transfer poverty rates suggests that while macroeconomic conditions are associated with the potential for deprivation through market income, final poverty outcomes show only weak links to the macro-financial variables monitored by the MIP scoreboard, consistent with the interpretation that country-specific tax-and-benefit institutions play a mediating role. Similarly, the complete absence of macro-financial predictors for the labour force participation rate suggests that this indicator may be linked to demographic shifts, education enrolment, migration, and policy reforms affecting retirement and childcare rather than to cyclical imbalances.

Our results can be situated within the broader literature on MIP indicator performance. Dany-Knedlik, Kämpfe, and Knedlik (2021), evaluating the MIP scoreboard for Central and Eastern European economies, find no statistically meaningful thresholds for labour-market indicators and recommend their exclusion from crisis-discrimination exercises. Our results are consistent with this finding: once macro-financial variables are accounted for, social indicators contribute limited additional predictive content in our out-of-sample framework. Regarding specific indicators, our results both confirm and qualify prior findings. Knedlik (2014) reports positive utility for unemployment at the original MIP thresholds, and in our framework, unemployment is predicted by the macro-financial block, particularly non-performing loans and unit labour costs. This pattern suggests substantial overlap in informational content between unemployment and selected macro-financial indicators, rather than indicating independent incremental predictive information.

Domonkos et al. (2017) identify the participation rate as one of the most relevant MIP indicators based on factor analysis. Our predictive framework offers a complementary perspective: the labour force participation rate shows no robust association with the non-social block across methods. This difference is consistent with the distinct objectives of the approaches: factor analysis summarises common co-movement across indicators, whereas we evaluate out-of-sample predictive relationships from the non-social block to social indicators.

Finally, while Bacchini, Ruggeri Cannata, and Donà (2020) conclude that social MIP indicators are useful for investigating well-being across Member States, our results are fully consistent with this interpretation. We do not argue that social indicators lack value; rather, our results suggest that

they remain important for welfare monitoring and for interpreting the social dimension of imbalances, while their incremental predictive information beyond the macro-financial (non-social) block appears limited within our framework.

Our results hold several **implications for European economic governance and social policy coordination**. Regarding MIP architecture, we recommend treating social indicators as complementary diagnostics rather than primary procedural triggers within the preventive arm. The MIP could continue reporting social outcomes to provide a holistic assessment, which remains politically essential given the need to highlight social distress, as demonstrated in post-crisis in-depth reviews. However, decisions to trigger warnings or corrective action should depend primarily on macro-financial indicators, with social metrics serving to contextualise severity and tailor policy responses. For instance, when macro indicators signal an imbalance alert, the severity of associated social indicators could guide whether recommended measures should include strengthened social protection measures or employment programmes.

Our findings also support establishing a **dedicated Social Convergence Framework** alongside the MIP. The near-zero predictability of post-transfer poverty from macroeconomic variables is consistent with the rationale for separate surveillance of social policies. Certain auxiliary social outcomes – such as severe material deprivation and very low work intensity (a proxy for labour market exclusion) – may be less amenable to uniform, threshold-based macro surveillance. These indicators are currently included in the MIP scoreboard as auxiliary items without formal thresholds (Appendix 1) and are therefore best interpreted as complementary diagnostics rather than threshold-based procedural triggers. A separate mechanism could monitor and address these challenges with appropriate tools, including targeted reforms, investment in social inclusion, and deployment of EU social funds. Such separation would allow the EU to pursue social objectives without diluting the MIP's core mandate of preventing macroeconomic crises.

At the national level, we document robust within-country associations between non-performing loans and unemployment, and between real GDP growth and lower youth disengagement and low work intensity indicating systematic co-movement between macro-financial indicators and selected social outcomes in the EU data. However, the link between macroeconomic conditions and social welfare is not uniform across all dimensions. The unpredictability of post-transfer poverty from macro variables indicates that factors such as the design of tax-and-benefit systems, income inequality, and regional disparities may weaken the association between aggregate growth and poverty outcomes (Knedlik 2014). Active labour market policies, education, and training are widely considered essential for broadly shared prosperity (Card et al. 2018), while strong automatic stabilisers are associated with smaller social costs of temporary shocks (Dolls, Fuest, and Peichl 2012).

Several **limitations** of this study warrant acknowledgement. Our analysis relies on annual scoreboard data, which may obscure higher-frequency dynamics relevant for early-warning purposes. Monthly or quarterly indicators, where available, could provide more granular insights into lead-lag relationships between macro-financial and social variables. Additionally, our panel approach treats EU member states as relatively homogeneous units within estimation. While we control for country fixed effects, remaining cross-country heterogeneity in labour market institutions, social protection systems, and economic structures may affect the stability and cross-country

generalisability of the estimated associations. Future research could employ regime-switching models or cluster-specific estimations to capture this heterogeneity more fully. We also focus on the existing MIP indicator set, whereas alternative social metrics, including measures of income inequality, housing affordability, or health outcomes, may exhibit different relationships with macro-financial conditions. Finally, our analysis cannot fully disentangle causation from correlation. While the patterns we observe are consistent with macro-financial conditions driving social outcomes, reverse causality is plausible for some relationships, as we note for non-performing loans and unemployment, and omitted variable bias cannot be definitively excluded.

In conclusion, this study demonstrates that the MIP's social indicators possess limited incremental utility as advance-warning signals once the non-social scoreboard is observed, while remaining vital as measures of societal well-being and as inputs into the broader assessment of imbalances. The key empirical contribution is to document pronounced heterogeneity in out-of-sample predictive performance: labour-market indicators and severe material deprivation achieve moderate-to-high R^2 in LOCO-CV when predicted from the non-social scoreboard, whereas post-transfer poverty exhibits near-zero out-of-sample predictability in our models. From a governance perspective, these results support monitoring both macro-financial conditions and social outcomes: macro-financial indicators contain predictive information relevant for several labour-market variables, whereas some poverty measures show only weak links to the non-social scoreboard and may require complementary analytical frameworks focused on social-policy and institutional factors. European economic governance could be strengthened by streamlining the MIP to focus on core macroeconomic risks while simultaneously developing parallel mechanisms, potentially a formalised Social Convergence Framework, to monitor and address social outcomes with appropriate expertise and political visibility. Such rebalancing would advance the ultimate aim of EU governance: not merely avoiding crises, but promoting a high-employment, socially inclusive Union without conflating causes and effects.

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Appendix 1. MIP scoreboard indicators*: main (1–13) and *auxiliary* (14–36)

No.	Variable	Description	Thresholds
1	CAB3	Current account balance – % of GDP, 3–year average	–4%/6%
2	NIIP	Net international investment position – % of GDP	–35%
3	REER3	Real effective exchange rate, 42 trading partners – 3-year % change	±3% (EA) / ±10% (non-EA)
4	EXP3	Export performance against advanced economies – 3-year % change	–3%
5	NULC3	Nominal unit labour cost index (per hour worked) – 3-year % change	9% (EA) / 12% (non-EA)
6	GGSD	General government gross debt – % of GDP	60%
7	HHDGDP	Household debt including non-profit institutions serving households, consolidated – % of GDP	55%
8	NFCD	Non-financial corporations' debt, consolidated – % of GDP	85%
9	HHCF1	Household credit flow including non–profit institutions serving households, consolidated – % debt stock (t – 1)	14%
10	NFCCF1	Non-financial corporations' credit flow excluding foreign direct investment, consolidated– % debt stock (t – 1), excluding foreign direct investment	13%
11	HPIN	House price index, nominal – 1 year % change	9%
12	**UR**	**Unemployment rate – % of labour force aged 15–74**	**10%**
13	**LFPR3**	**Labour force participation rate – 3–year change in pps (% of population aged 15–64)**	**–0.2%**
14	*NIIPE*	*Net international investment position excluding non-defaultable instruments – % of GDP*	
15	*NLB*	*Net lending / borrowing (current account + capital account) – % of GDP*	
16	*NTBEP*	*Net trade balance of energy products – % of GDP*	
17	*RGDP*	*Real GDP per capita – EUR*	
18	*GFCF*	*Gross fixed capital formation – % of GDP*	
19	*GDERD*	*Gross domestic expenditure on R&D in % of GDP*	
20	*EMS3*	*Export market share (% of world exports), in volume – 3-year % change*	
21	*LP1*	*Labour productivity (per hour worked) – 1-year % change*	
22	*CID*	*Core inflation differential vis-à-vis the euro area – pps*	
23	*HHDGDI*	*Household debt including non-profit institutions serving households, consolidated –% of Gross Disposable Income*	
24	*GNPL*	*Gross non-performing loans of domestic and foreign entities – % of gross loans*	

No.	Variable	Description	Thresholds
25	*T1CR*	*Tier-1 capital ratio of banking sector – % of risk-weighted assets*	
26	*ROEBS*	*Return on equity of banking sector – %*	
27	*SHPIR*	*Standardised house price-to-income ratio – % of long-term average (2000 – current)*	
28	*BP*	*Building permits – m² per 1000 inhabitants*	
29	***LTUR***	***Long-term unemployment rate – % of labour force aged 15–74***	
30	***YUR***	***Youth unemployment rate – % of labour force aged 15–24***	
31	***ER***	***Employment rate – % of total population aged 20–64***	
32	***YPEE***	***Young people neither in employment nor in education and training – % of total population aged 15–29***	
33	***PRPE***	***People at risk of poverty or social exclusion – % of total population***	
34	***PRPEST***	***People at risk of poverty after social transfers – % of total population***	
35	***SMDP***	***Severely materially deprived people – % of total population***	
36	***PLH***	***People living in households with very low work intensity – % of total population aged 0–64***	

* Social MIP: in bold.

Source: Eurostat 2025.

Appendix 2. Description of social MIP (*auxiliary indicators in italics*)

Social indicator	Description
12. Unemployment rate (% of labour force aged 15–74)	The unemployment rate is the number of people unemployed as a percentage of the labour force. Unemployed persons comprise persons aged 15 to 74 who fulfil all the three following conditions: were not employed during the reference week; are available to start work within the next two weeks following the reference week and have been actively seeking work in the past four weeks preceding the reference week or have already found a job to start within the next three months. The MIP Scoreboard indicator is the number of unemployed persons aged 15–74 as a percentage of the labour force and is calculated as: $[U_t / LF_t]$. The indicative threshold is 10%.
13. Labour force participation rate (3 y pps change, % of total population aged 15–64 years)	The labour force participation rate is the percentage of economically active population aged 15–64 on the total population of the same age. The International Labour Organisation (ILO) for the purposes of labour market statistics classifies as employed, unemployed and outside the labour force. The economically active population (also called labour force) is the sum of employed and unemployed persons. Persons outside the labour force are those who are neither employed nor unemployed. The MIP Scoreboard indicator is the 3-year change in percentage points, with an indicative threshold of –0.2 pp.

Social indicator	Description
29. Long-term unemployment rate (% of labour force aged 15–74)	*The long-term unemployment rate is the number of persons unemployed for 12 months or longer as a percentage of the labour force (i.e. economically active population aged 15–74).*
30. Youth unemployment rate (% of labour force aged 15–24)	*The youth unemployment rate is the unemployment rate of people aged 15–24 as a percentage of the labour force of the same age.*
31. Employment rate (% of population aged 20–64)	*The employment rate of the total population is calculated by dividing the number of person aged 20 to 64 in employment by the total population of the same age group. The indicator is based on the EU Labour Force Survey.*
32. Young people neither in employment nor in education and training (% of total population aged 15–29)	*The indicator Young people Neither in Employment nor in Education and Training (NEET) provides information on young people (15–29 years) who meet the following two conditions: (a) they are not employed (i.e.źunemployed or inactive according to the ILO), and (b) they have not received any education or training in the four weeks preceding the survey.*
33. People at risk of poverty or social exclusion (% of total population)	*This indicator (AROPE) corresponds to the proportion of persons who are at risk of poverty, or severely materially deprived, or living in households with very low work intensity. Persons are only counted once even if they are present in several sub-indicators.*
34. People at risk of poverty after social transfers (% total population)	*The indicator measures the proportion of persons with an equalised disposable income below the risk-of-poverty threshold, which is set at 60% of the national median equalised disposable income (after social transfers) as a % of total population.*
35. Severely materially and socially deprived people (% total population)	*Severely materially and socially deprived persons have living conditions severely constrained by a lack of resources, such that they experience an enforced lack of at least 7 out of 13 deprivation items: i) capacity to face unexpected expenses, ii) capacity to afford paying for one week annual holiday away from home, iii) capacity to being confronted with payment arrears (on mortgage or rental payments, utility bills, hire purchase instalments or other loan payments), iv) capacity to afford a meal with meat, chicken, fish or vegetarian equivalent every second day, v) ability to keep home adequately, vi) have access to a car/van for personal use, vii) replacing worn-out furniture, viii) having internet connection, ix) replacing worn-out clothes by some new ones, x) having two pairs of properly fitting shoes (including a pair of all-weather shoes), xi) spending a small amount of money each week on him/herself, xii) having regular leisure activities, or xiii) getting together with friends/family for a drink/meal at least once a month.*
36. People living in households with very low work intensity (% of population aged 0–64)	*People living in households with very low work intensity are people aged 0–59 living in households where the adults (aged 18–59) worked less than 20% of their total work potential during the past year. Students are excluded.*

Source: Eurostat 2025.

Comparative Economic Research. Central and Eastern Europe
Volume 29 Number 3, 2026
https://doi.org/10.18778/1508-2008.29.19

Reshaping Fiscal Federalism: Adaptive Responses in the Era of Polycrisis – Empirical Evidence from European Countries

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Abstract

Fiscal federalism has evolved significantly in response to complex crises affecting the balance between decentralization and centralization in governance. The COVID-19 pandemic, geopolitical conflicts, climate change, financial instability, and demographic shifts have prompted adaptive governance, including temporary recentralization, increased fiscal transfers, and flexible policy responses. This article examines adjustments to fiscal decentralization models in selected European countries, exploring the financial frameworks of subnational governments (SNGs). The study analyses the relationship between the size of the local government sector and economic indicators such as GDP per capita, unemployment, and GDP growth from 1995 to 2023, covering economic disruptions including the 1998 and 2008–2009 global financial crisis and the 2020–2022 COVID-19 pandemic across 25 European countries. A subsequent cluster analysis categorizes countries based on their fiscal federalism models, using SNG fiscal indicators to assess their adaptability to crises. Findings suggest that countries with SNGs that actively invest and moderately redistribute achieve better long-term economic performance.

Keywords: polycrisis, fiscal federalism, decentralization, subnational government finance, governance adaptation

JEL: H11, H12, H70, H77, H83

Funding information: This research was funded by the Minister of Science under the 'Regional Initiative of Excellence' (RID) programme. The grant was awarded to the Department of Finance within the Faculty of Economics and Finance at the University of Bialystok.
The percentage share of the Authors in the preparation of the work is: K.K. – 50.00%, M.P. – 50.00%.
Conflicts of interests: None.
Ethical considerations: The Authors assure of no violations of publication ethics and take full responsibility for the content of the publication.
Received: 12.12.2025. Verified: 26.01.2026. Accepted: 24.06.2026

Introduction

The concept of fiscal federalism is evolving significantly in response to the contemporary era marked by multiple crises (polycrisis). These include challenges such as the COVID-19 pandemic, climate change, financial instabilities, migration issues, and geopolitical conflicts, all of which have profound implications for the functioning of multilevel public finance systems. Fiscal federalism, traditionally focused on the allocation of roles and responsibilities for public finances and services across different government levels, now requires reevaluation to address the complexities of these crises and the necessary coordination of public policies.

In recent times, many decentralized states have temporarily shifted to centralized management of crises to facilitate quick resource mobilization, efficient aid distribution, and the uniform implementation of large-scale safety measures, especially evident during the COVID-19 pandemic's healthcare responses and economic interventions. Simultaneously, traditional fiscal constraints on deficits and public debt were often relaxed or suspended, enabling increased government spending to address the crisis-related impacts. This flexibility in fiscal policy underscores the need for adaptive fiscal governance during such turbulent times.

Moreover, the structure of public expenditures has shifted significantly, prioritizing public health, unemployment support, and aid for sectors most affected by the crises. This adjustment highlights the crucial role of fiscal federalism in resource allocation during emergencies. The importance of enhanced cooperation among different government levels has also become apparent, as effective coordination is essential for managing public health crises and economic measures. In several instances, these crises have spurred new forms of intergovernmental collaboration.

Additionally, fiscal transfers between government levels have become more critical, with central governments often providing additional funds to lower levels tasked with crisis response measures such as testing, vaccinations, and supporting businesses. While these transfers have bolstered local budgets, they have also prompted concerns over their equitable distribution and efficient use. In the European Union (EU), initiatives like the Recovery Fund (Next Generation EU) played a pivotal role in the fiscal response to the crisis.

The overlapping nature of these crises has further compounded fiscal imbalances and escalated public debt, with governments increasingly relying on borrowing, thus raising concerns over long-term fiscal sustainability and fair financial burden-sharing across regions. Modern crises have also underscored the need for robust, adaptable, and well-managed governmental institutions capable of swiftly responding to changing circumstances, efficiently allocating resources, and maintaining public trust.

The objective of this article is to assess how the era of polycrisis has reshaped the theoretical foundations of fiscal federalism and to analyze how selected European countries have adapted their multilevel public finance systems to address crisis management challenges. We also aim to identify different models of fiscal federalism in the context of the diverse fiscal responses of the subnational government (SNG) sector in the studied countries to emerging crises.

Against this background, the present study contributes to a growing but still fragmented literature on how fiscal federalism systems adapt to multiple, overlapping crises. Existing empirical studies usually

focus on single crisis episodes, such as the global financial crisis, the COVID-19 pandemic, or periods of fiscal stress. These analyses are typically conducted over short time horizons or within individual countries or regional settings. Consequently, there is still a lack of long-term comparative research that examines how SNG systems evolve in response to a sequence of interacting crises.

Moreover, the empirical literature rarely uses typological approaches based on cluster analysis to identify models of fiscal federalism that account simultaneously for the size, functional structure, and macroeconomic relevance of the SNG sector. In particular, limited attention has been paid to the relationship between the fiscal orientation of SNGs, especially the balance between redistributive and investment functions, and long-term economic performance across different crisis phases.

This study addresses these gaps by providing a long-term comparative empirical analysis for the period 1995–2023 and by identifying distinct models of fiscal federalism in Europe under conditions of polycrisis. By combining correlation analysis with cluster classification, this article identifies stable empirical patterns and reveals heterogeneous adaptive trajectories of SNGs. In this way, it contributes to a better understanding of fiscal federalism in an environment of heightened and persistent uncertainty.

For the empirical analysis, statistical correlation and cluster analysis methods were employed, based on fiscal indicators from 24 EU member states and Norway between 1995 and 2023. The research aims to provide empirical insights that offer practical recommendations for optimizing fiscal federalism in the context of global crises, contributing to the ongoing debate on the balance between centralization and decentralization, as well as the effectiveness of public governance in an uncertain and dynamically evolving environment.

Literature Review

Fundamental Principles of Fiscal Federalism and Their Evolution in the Scholarly Literature

Fiscal federalism represents a contemporary economic concept that directly challenges centralism, functioning within the framework of multilevel public finances. This concept emphasizes determining the optimal extent of fiscal decentralization, which requires a careful balance of political rights, competencies, tasks, and public funds across various levels of government (Poniatowicz 2018). The decentralization process involves transferring powers, duties, and resources from the central government to lower levels of authority, with local governments acting as the primary agents of this decentralized administration (Poniatowicz, Konopka, and Piekutowska 2024). Fiscal federalism advocates for a systematic division of public authority, highlighting the associated redistribution of public revenues and expenditures, as well as the governance connected to them. Although the term "federalism" might suggest applicability solely to countries with a federal structure, this is not the case. In fact, fiscal federalism is relevant to both federal and unitary states, assuming their public finance systems are decentralized (Poniatowicz 2023).

Building on this framework, the sub-discipline of fiscal federalism explores how the structure of a country's financial system interacts with the functioning of its public institutions and their intergovernmental

relations (IGR). This approach emphasizes the importance of well-coordinated intergovernmental dynamics in enhancing the effectiveness and efficiency of government at all levels.

Literature identifies several positive outcomes of well-formed IGR among different levels of public authority (Heinemann-Grüder et al. 2017):

- The decentralization of the decision-making process and the functional empowerment of local governments through the assignment of competencies and resources suitable for the public tasks they undertake.
- Increased transparency in the public finance sector and enhanced effectiveness in the decision-making processes of public policymakers.
- Ongoing dialogue between various levels of public authority.
- The inclusion of a wider range of perspectives and public objectives in policy-making, facilitated by intergovernmental cooperation and consensus, which consequently strengthens the integration of such policies, as well as acceptance and respect for the rule of law.
- Enhanced coherence of public policy with the federal principle of "unity in diversity," which acknowledges that variations in territorial policies are acceptable and that the role of intergovernmental coordination is to ensure the functionality of the system as a whole.

Another positive aspect that is emphasized in the literature is the impact of fiscal decentralization on economic growth (Mali and Maličká 2021; Makreshanska Mladenovska, and Tashevska 2024). Nonetheless, some authors argue that the lack of appropriate theoretical frameworks undermines the validity of empirical studies on this subject. In their opinion, a fair summary of empirical research on the direct relationship between fiscal decentralization and economic growth indicates that it remains an open question (Martínez-Vazquez and McNab 2001). Other authors, in turn, analyze the positive impact of public investments, including investments by local government units, on economic growth and resilience to external economic shocks (Jarosiński 2023; Danaj and Reçi 2024; Matić 2024).

Fiscal federalism and the associated decentralization of public authority, while offering many advantages, also present significant challenges. The literature frequently highlights the difficulties stemming from the complex structure of multilevel public governance, which can lead to tensions and conflicts between different levels of authority. Such situations are often described as an "intergovernmental tug-of-war" (Ryan 2012; Purnell 2019). This issue becomes particularly evident during crises, when various levels of public authority pass responsibility for decisions, or their absence, back and forth. This phenomenon, known as the "blame game," underscores the challenges in assigning accountability in decentralized systems (Hood 2011; Hinterleitner 2017).

Moreover, decentralization can lead to issues related to inconsistency and inadequate coordination of activities at the regional and local levels. The absence of uniform standards or the duplication of efforts by different territorial units can result in inefficiencies in the execution of public policies (Treisman 2007; Bardhan 2022).

Another challenge is the increase in administrative costs. Distributing competencies across various levels of authority necessitates the creation of additional organizational structures, which can lead to higher operational expenses and an expansion of the public sector (Bodman and Ford 2006).

Decentralization also means forgoing economies of scale. Fragmenting competencies into smaller territorial units often hampers the potential savings that could be achieved from larger administrative structures (Wieliczko 2018).

Decentralization also poses a risk of exacerbating interregional inequalities. Wealthier regions have a greater potential to generate revenue from local taxes, which enables them to better fund public services. Conversely, less affluent areas often remain underfunded, perpetuating disparities in the standard of living among residents (Feld et al. 2021).

Some studies also identify the occurrence of external effects (spillover effects) when decisions made by one administrative unit adversely affect others, such as in environmental protection or infrastructure. The lack of effective cooperation between levels of authority can lead to the neglect of these issues, which in turn reduces the quality of public services (Oates 1999; Boadway and Shah 2009).

The risk of increased corruption in decentralized systems cannot be overlooked either. Without adequate monitoring and control mechanisms, local authorities may be more prone to corrupt practices, negatively impacting the efficiency and transparency of public governance (Fisman and Gatti 2002; Shah 2007).

These challenges demonstrate that while decentralization offers many benefits, it also requires thoughtful public management and proper coordination to minimize its potential drawbacks.

Fiscal federalism theory seeks to identify the optimal level of decentralization and the division of financial functions across various levels of authority, from central to local. Richard A. Musgrave (1959) emphasizes that the central government should manage economic stabilization and income redistribution, while local governments should oversee the efficient allocation of resources.

Contemporary concepts like multilevel governance (MLG) stress the importance of optimally matching competencies and resources to functions, as seen in the functional, overlapping, and competing jurisdictions (FOCJ) model. Developed by Bruno Frey and Reiner Eichenberger (1999), this idea posits that decentralization promotes efficiency and competition among territorial units only under these conditions.

Charles M. Tiebout (1956), a pivotal theorist in decentralization and a mainstay of fiscal federalism, promoted "foot voting", arguing that competition among local government units enhances the quality of local public goods. This mechanism allows residents to select local governments offering an optimal balance of public service quality and tax levels.

Fiscal federalism has evolved significantly as a theoretical concept, moving beyond traditional frameworks. First-generation fiscal federalism (FGFF) focused on the decentralization of allocative functions, assuming public authorities' rationality in decision-making. Second-generation fiscal federalism (SGFF) introduced a more complex approach, incorporating factors like institutions, transaction costs, and political interests for a more realistic perspective on public financial management.

Despite these diverse approaches, the core dilemmas of fiscal federalism theory, aptly identified by Richard M. Bird (2003), remain:

- Who should perform which public tasks to optimize public expenditures? – a question about expenditure assignment.
- Who should collect which taxes? – a question about revenue assignment.
- How can vertical disparities in income and public expenditures in the local government sector be mitigated? – addressing vertical fiscal imbalances.
- Should horizontal imbalances between the needs of territorial communities and their varied resource potentials be balanced, and if so, how? – addressing horizontal fiscal imbalances.
- Who should set the principles for limiting or controlling local government debt? – a question about local debt rules.
- What should the institutional system look like to optimally address the issues outlined in questions 1–5? – a question about the institutional aspects of fiscal federalism.

These questions remain central to the debate on fiscal federalism. Each country should analyze and address these dilemmas individually, given that there is no universal model of fiscal federalism (Sorens 2011). Differences in institutional structures, political traditions, levels of decentralization, and regional economic and social conditions mean that effective solutions in one country might be inadequate in another. For instance, the challenges of fiscal federalism in federal states like Germany or the United States differ from those in unitary states like Poland or France. The historical context and political culture also significantly influence cooperation and negotiation among various levels of authority (Bird and Vaillancourt 2006).

An individual approach also requires a detailed analysis of specific challenges arising from dynamically changing global conditions and the simultaneous occurrence of various crises (the concept of global polycrisis to be discussed later). Crisis conditions vary based on geographical location, economic structure, and the social development level of individual countries. For instance, highly developed countries must balance fiscal stability with investments in sustainable development, while developing countries focus on combating regional inequalities and financing essential public infrastructure (Oates 1999; Boadway and Shah 2009).

The absence of a universal fiscal federalism model compels countries to continuously experiment and adapt their systems. This process should be grounded in empirical evidence, enabling the assessment of the effectiveness of actions taken and the identification of best practices.

Conceptual Reshaping of Fiscal Federalism in a Crisis Context

The contemporary world is characterized by a proliferation of crises (Mączyńska 2021), encompassing the following phenomena:

- An increase in the number of crises – modern societies face more frequent crises than in the past, attributed to factors such as globalization, technological advancement, and climate change.
- Interconnections between crises – crises often interconnect (for instance, a climate crisis may lead to a migration crisis, which in turn triggers socio-political tensions and affects the economy).

- The intensification of crisis impacts – crises are not isolated; their effects permeate various aspects of socio-economic life, often exacerbating their impact.
- Complexity of solutions – due to the interplay of crises, resolving them requires more complex, interdisciplinary, and international approaches.

The term "polycrisis," linked to the phenomenon of crisis multiplication in the contemporary world, was first coined by French philosopher and sociologist Edgar Morin (2001) in his book "La Méthode. 5, L'humanité de l'humanité". Morin employed this concept to describe the coexistence and mutual penetration of numerous crises that merge into a global, intricate network of challenges.

In recent years, the term has gained traction and has been elaborated upon by various institutions, such as the International Monetary Fund (2023), and scholars like Adam Tooze (2022). Tooze has become one of the prominent proponents of this term in the English language. His contributions have greatly advanced the application of the concept in the fields of social sciences and public policy. He has redefined "polycrisis" to denote contemporary global crisis challenges, highlighting their complexity and interdependency, as illustrated in Figure 1.

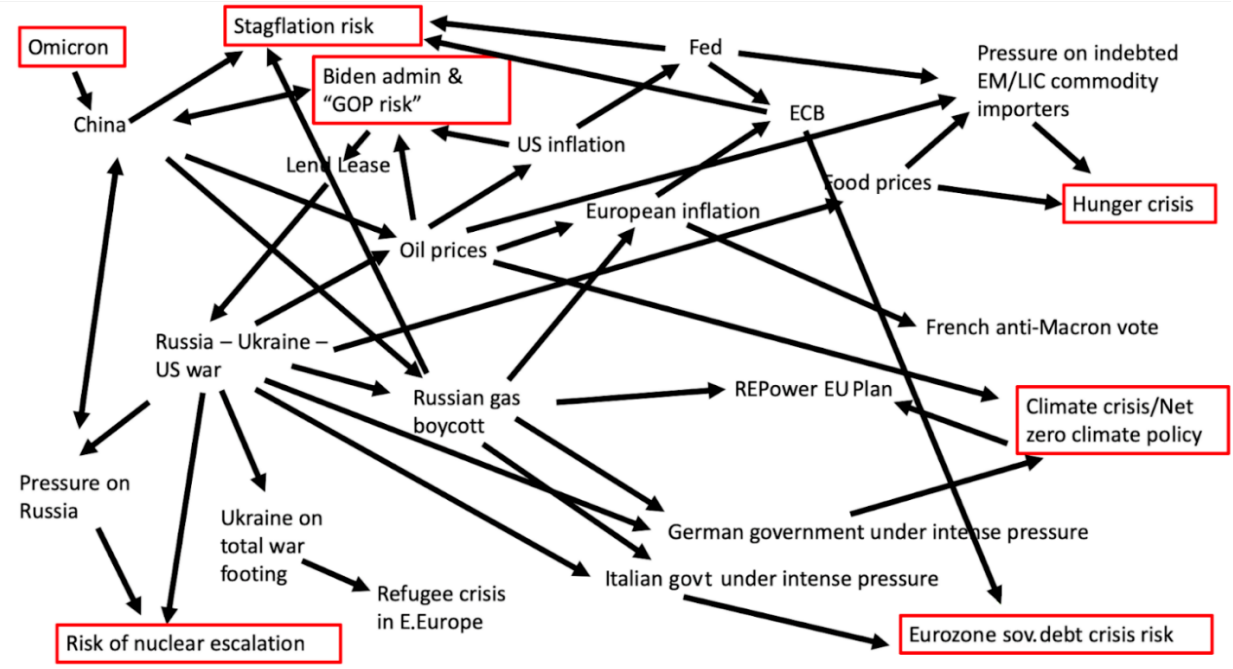

Figure 1. Model of the multifaceted impact of global crises in the context of a polycrisis
Source: adapted from Tooze 2022.

In the context of overlapping crises, recent studies on fiscal federalism move beyond the question of the optimal degree of decentralization and increasingly focus on the resilience, adaptive capacity, and coordination properties of multilevel fiscal systems (see Table 1).

The COVID-19 crisis presented a major challenge to fiscal federalism and public finances worldwide. The pandemic emerged in December 2019, with the first cases reported in Wuhan, China, and quickly spread across the globe, triggering a severe health and economic crisis. This crisis persisted throughout 2020, with its primary economic repercussions extending into 2021 and 2022. The pandemic resulted in a significant deterioration of public finances, marked by increased

government spending and declining tax revenues (Wildowicz-Szumarska 2021; Vinhas de Souza 2024). A key characteristic of this period was the "covidization" of public finances, defined by the widespread use of extraordinary economic policy measures, commonly known as stimulus packages (Agrawal and Bütikofer 2022).

Both fiscal and monetary policies played a crucial role in mitigating the crisis. On the monetary side, central banks lowered interest rates, implemented quantitative easing, and engaged in "helicopter money" strategies injecting liquidity directly into the economy to counteract economic downturns. On the fiscal side, governments introduced expansive anti-crisis measures, such as increased public spending and tax reductions, designed to stimulate economic activity and mitigate the adverse effects of the pandemic. These interventions highlighted the benefits of a flexible fiscal approach while also exposing the challenges and risks associated with long-term fiscal instability during global crises.

Table 1. Recent research on fiscal federalism in the context of polycrisis

Author (year)	Crisis context	Key findings for fiscal federalism	Implications for the analytical framework of this study
Brosio (2024)	Global risks, increasing crisis complexity, erosion of classical theoretical frameworks	Traditional fiscal federalism assumptions based on stable macroeconomic conditions and a clear functional division erode under sequential crises. Central tension arises between fiscal centralization and the preservation of subnational autonomy and accountability.	Offers theoretical justification for moving beyond FFF/SGFF towards an adaptive understanding of fiscal federalism requiring institutional recalibration rather than simple recentralization.
Dougherty and Mota (2024)	Multi-dimensional crises, competence conflicts, fiscal stress	Crises intensify intergovernmental conflicts; the effectiveness of fiscal federalism depends on the quality of institutionalized coordination and co-operation mechanisms across government levels.	Supports the article's focus on intergovernmental relations as a core determinant of system resilience.
Edwards (2024)	Public debt crisis	Excessive centralization contributes to debt accumulation; federal arrangements may serve as a fiscal discipline mechanism.	Provides a theoretical counterpoint highlighting the tension between fiscal stabilization and budgetary discipline in multilevel systems.
Dougherty, Montes Nebreda, and Urrutia (2025)	Post-COVID fiscal consolidation, high public debt	Intergovernmental transfers retain stabilization functions during crises, but their equalization capacity weakens under fiscal consolidation pressures.	Justifies the analysis of the resilience of decentralization models under sequential crises and fiscal constraints.
Herrero-Alcalde, Martín-Román, and Moral-Arce (2025)	COVID-19 pandemic; extraordinary fiscal interventions	Different dimensions of decentralization generate divergent crisis responses: expenditure autonomy constrains the scale of fiscal intervention, whereas borrowing autonomy tends to amplify it.	Provides direct justification for moving beyond aggregate decentralization indicators and focusing on the institutional and financial structure of the SNG sector.

Author (year)	Crisis context	Key findings for fiscal federalism	Implications for the analytical framework of this study
Martínez-Vazquez (2025)	Sequential and overlapping crises (pandemic, climate change, economic shocks); erosion of stable macroeconomic conditions	Classical models of fiscal federalism (FGFF and SGFF) are insufficient under contemporary crisis conditions. The author calls for a "third-generation fiscal federalism" integrating fiscal, administrative, and political dimensions, as well as adaptive and coordination mechanisms.	Provides a strong theoretical foundation for treating fiscal federalism as an evolving and adaptive system, directly legitimizing the analytical framework of the article.
Shrestha and Hankla (2025)	Fiscal crises, COVID-19 pandemic, macroeconomic instability	The effects of decentralization are highly context-dependent; there is no single "optimal" model of fiscal federalism that is universally crisis-resilient.	Reinforces the need for an empirical typology of decentralization models and for analysing their differentiated resilience under polycrisis conditions.
Shafi and Mallinson (2026)	Political crises, party fragmentation, complex decision-making environments	The functioning of federal systems under crisis conditions is strongly shaped by political configurations. System performance depends on interactions between fiscal institutions and party systems rather than on the formal allocation of competences alone.	Supports the argument that fiscal federalism should be analysed as an adaptive system incorporating political and institutional conditions.

Source: own elaboration.

The pandemic had a profound impact on the finances of the SNG sector, creating what is often referred to as the "pandemic scissors effect" (Poniatowicz 2022). This phenomenon resulted from a simultaneous surge in expenditures (due to increased health, social, and economic support measures) and a decline in budget revenues caused by the socioeconomic effects of the crisis. Many local government units experienced severe financial strain as they struggled to balance these opposing fiscal pressures.

In response, numerous countries temporarily shifted fiscal competencies toward centralization, allowing for the rapid mobilization of resources and the implementation of uniform regulations[1]. This shift highlighted the need for effective intergovernmental cooperation and the creation of a resilient financial system capable of adapting to rapidly changing circumstances. The crisis underscored the importance of ensuring that SNGs have the necessary financial tools to respond effectively to future shocks while maintaining fiscal stability.

Financial crises, such as the 1998 financial crisis and the 2008 global financial crisis, along with contemporary challenges related to inflation and rising public debt, highlight the need for a reassessment of public finance management principles. Fiscal transfer mechanisms and consolidation rules must be more adaptable to rapidly changing economic conditions. Fiscal transfers, which involve reallocating

1 Unfortunately, in some countries, such as Poland, the pandemic was used as a pretext to weaken democracy and systematically curtail the financial autonomy of local government units, which is recognized in doctrine as a fundamental pillar of fiscal federalism. The local government finance system became increasingly reliant on earmarked grants distributed by central authorities based on political criteria. This process was characterized by arbitrariness, discretionary decision-making, and a lack of transparency, raising significant controversy and concerns about its fairness and accountability (Poniatowicz 2022).

funds between different levels of government, should be designed with greater flexibility to ensure that local crises can be managed effectively without compromising the stability of the overall public finance system. At the same time, the fiscal consolidation process, aimed at reducing budget deficits and public debt, must be carefully structured to avoid hampering economic growth.

The first of these crises began in July 1997, when a sudden capital outflow and currency depreciation disrupted the economies of Southeast Asia (Krugman 1998). The Asian financial crisis led to a sharp decline in investor confidence in emerging markets, triggering a domino effect across global financial markets. This crisis contributed to widespread financial instability, which also impacted Europe. However, European financial difficulties had additional, distinct causes, including the costs of German reunification, the economic transition in Central and Eastern Europe, financial market tensions related to the introduction of the euro, and the 1998 Russian financial crisis. In the SNG sector, the crisis primarily manifested as an economic slowdown, resulting in declining local tax revenues and increasing restrictions on external financing. The latter was driven by stricter lending conditions imposed by banks, which constrained the ability of local governments to fund public services and infrastructure projects.

The second major crisis, which originated in the United States in 2007 due to turmoil in the mortgage lending market, quickly engulfed global markets (Reinhart and Rogoff 2009). Peaking in 2008 and extending through 2009, its economic repercussions reshaped global economic and financial policies for years. For the SNG sector, the impact was severe and multifaceted. The economic downturn significantly reduced local tax revenues, weakening the capacity of local governments to support public services and infrastructure. Concurrently, the demand for social services, including unemployment support and assistance for low-income individuals, surged, placing additional strain on local budgets. To cope with these challenges amid falling revenues, many local governments were compelled to increase borrowing or restructure existing debts, exacerbating their financial fragility and exposing the vulnerabilities of decentralized public finance systems. This crisis underscored the need for more resilient fiscal frameworks capable of absorbing economic shocks while ensuring long-term financial sustainability.

Amid these economic disruptions, another pressing issue emerged the climate and environmental crises (IPCC 2023) further underscoring the urgent need for a coordinated approach to public policy at the international, national, and subnational levels. The increasing frequency of extreme weather events, rising sea levels, biodiversity loss, and resource depletion are placing growing pressures on public finance systems to fund both adaptation and mitigation efforts. These environmental challenges not only threaten economic stability but also deepen social inequalities, as the most vulnerable populations are disproportionately affected by climate-related disasters. Meeting the Sustainable Development Goals (SDGs) requires effective collaboration between different levels of government to ensure that responsibilities and resources are distributed fairly among national, regional, and local authorities. Policymakers must find a balance between top-down climate policies, which provide strategic direction and funding, and bottom-up initiatives, which allow for regionally tailored solutions that respect local autonomy.

Addressing the financial pressures linked to the climate crisis calls for innovative fiscal instruments, including green bonds, carbon pricing mechanisms, and climate-resilient public investment strategies.

With an increasing emphasis on sustainable finance, there is a growing need for transparency and accountability in how public funds are allocated to climate-related initiatives. In the long run, tackling climate and environmental crises will require a holistic approach to public finance management one that integrates fiscal policies with long-term environmental goals while ensuring economic resilience and social equity in an era of accelerating ecological challenges.

The energy crisis is another formidable challenge that impacts how public finance systems function. Escalating energy prices, resource shortages, and increased reliance on energy imports have become particularly evident in recent years, especially in the context of the conflict in Ukraine. This crisis requires governments to undertake substantial investments in renewable energy development, improvements in energy efficiency, and the pursuit of energy independence through the diversification of resource supplies. In many cases, energy subsidies for households and businesses have also become imperative to alleviate the impact of rising living and operational costs. Simultaneously, governments must carefully balance these expenditures with long-term fiscal objectives to prevent the destabilization of public finances.

Demographic crises, driven by aging populations or uneven population distributions, exert pressure on public budgets. Addressing these issues requires reforming the financing of pension systems, healthcare, and social policies. Amid these challenges, adjusting fiscal transfers is vital both to support regions losing young labor forces and to ensure balanced funding for public services (European Commission 2024).

Migration crises, arising from armed conflicts, climate change, or economic inequalities, further strain public management structures at various levels. These crises necessitate flexible and effective response mechanisms within federal systems (UNHCR 2023).

Geopolitical crises, such as the conflicts involving Russia and Ukraine or Israel and Hamas, necessitate a significant increase in defense spending (Tran and Vo 2024). Strategic investment in border regions, which act as the first line of defense during emergencies, is of paramount importance. Fiscal transfers to these areas are indespensible not only for enhancing their defensive capabilities but also for ensuring the infrastructure and preparedness needed to effectively address geopolitical challenges.

Our empirical research, which will be explored more extensively later in this paper, covers nearly three decades and captures the impacts of three major crises: the 1998 financial crisis, the 2008–2009 global financial crisis, and the economic crisis induced by the COVID-19 pandemic from 2020 to 2022.

Those crises challenged the traditional principles of fiscal federalism. In the literature, the concept of "crisis federalism" has gained increasing attention. It refers to the application of federalism principles in extraordinary crisis situations, where the standard mechanisms for distributing power and responsibilities across different levels of government must be adjusted to respond more effectively to emerging challenges.

This perspective includes studies on changes in fiscal relations across government levels during crises (Blöchliger et al. 2010), the temporary recentralization of fiscal competencies in crisis situations (Canavire-Bacarreza, Evia Salas, and Martínez-Vazquez 2021), the management of rising subnational fiscal risks (de Mello and Ter-Minassian 2024), the impact of the COVID-19 pandemic

on fiscal governance (OECD 2021; World Bank 2021; Yilmaz and Boex 2021; Franek 2023), multilevel fiscal management of the green transition (Dougherty and Montes Nebreda 2023), geopolitical crises and their effects on changes in intergovernmental fiscal relations (International Monetary Fund 2022), and the resolution of intergovernmental fiscal disputes in times of crisis (Dougherty and Mota 2024). Table 2 summarizes the main challenges and dilemmas of fiscal federalism in the context of the polycrisis.

Table 2. Key challenges and dilemmas of fiscal federalism in the era of polycrisis

Dilemma/challenge	Description
Centralization vs. decentralization	Polycrisis necessitates rapid and coordinated responses, often leading to the centralization of power and resources. Simultaneously, decentralization is essential for effectively addressing local needs, particularly in crises such as natural disasters or migrations. Balancing these approaches is challenging, as too much centralization may curtail local autonomy, while excessive decentralization can cause a lack of policy coordination and coherence.
Resource distribution	Polycrisis aggravates regional disparities. As crises affect regions differently, fiscal federalism confronts the dilemma of allocating resources efficiently to both mitigate regional inequalities and ensure equitable access to resources.
Prioritization of public spending	Crises like the COVID-19 pandemic or armed conflicts necessitate substantial increases in spending on healthcare, armaments, and refugee support. Concurrently, significant investments are needed in sustainable development and infrastructure. Polycrisis complicates the budgetary prioritization, requiring a balance between immediate needs and long-term developmental objectives.
Fiscal transfers	Fiscal transfers are crucial for alleviating crisis effects. The challenge lies in designing transfers that are equitable, proportional to needs, and effective in the most impacted regions.
Intergovernmental coordination	The complexity of modern crises demands robust cooperation across government levels. Polycrisis highlights the need to enhance coordination mechanisms to prevent jurisdictional conflicts and ensure public action coherence. A primary dilemma is aligning the varying interests of local, regional, and central authorities.
Fiscal flexibility vs. fiscal stability	Crises prompt the need for dynamic adjustments in public budgets, calling for fiscal flexibility. Yet, enduring crises, such as the climate crisis, risk financial destabilization. The challenge is to balance swift crisis responses with maintaining long-term fiscal stability.
Economies of scale vs. local conditions	Global crises often necessitate large-scale measures, like mass vaccine purchases or constructing shared energy infrastructure. However, local needs differ greatly due to regional characteristics. The challenge is to blend the efficiency benefits of economies of scale with diverse local conditions and priorities.
Crisis management and public debt	Financing measures for crisis situations, like economic support during pandemics or increased defense spending during geopolitical crises, results in higher public debt. The dilemma is financing these measures without risking long-term financial instability.

Source: own elaboration.

In the context of the crisis challenges outlined in the table, fiscal federalism not only serves as a theoretical concept but also as a practical tool for designing and implementing public policies. Its effectiveness hinges on the ability to adapt to the unique conditions of each country and to respond dynamically to rapidly evolving challenges. Recent global crises have illuminated both the strengths and limitations of this concept, underscoring the importance of balancing decentralization and centralization for effective and sustainable public management.

Methodology and Results

The empirical research covered 24 EU member states and Norway. Cyprus, Luxembourg, and Malta were excluded as they are very small countries with populations below 1 million. Norway was included despite not being a member of the EU primarily due to its distinctive municipal features and the availability of comprehensive statistical data on the SNG sector[2]. Norway's governance system is characterized by a high degree of decentralization and strong local autonomy, making it a compelling case for analysis within the context of fiscal federalism. Including this country in the analysis enhances our understanding of the diversity of governance models in Europe and their impact on local economies and fiscal policies.

The research spanned from 1995 to 2023 and was divided into nine sub-periods, each corresponding to the pre-crisis, crisis, and post-crisis phases of three major economic disruptions: the 1998 financial crisis, the 2008–2009 global financial crisis, and the 2020–2022 pandemic economic crisis. The sub-periods identified for these analyses were:

1) 1995–1997 – the pre-1998 financial crisis period;
2) 1999–2000 – the 1998 financial crisis period;
3) 2001–2004 – a period of economic stabilization and the prelude to the next financial shock;
4) 2005–2007 – the pre-2008 financial crisis period;
5) 2009–2010 – the 2008 global financial crisis period;
6) 2011–2015 – a period of restoring trust in financial institutions and political adjustment post-crisis;
7) 2016–2019 – a period of relative economic stability and growth before the COVID-19 pandemic;
8) 2020–2022 – the global COVID-19 pandemic crisis period;
9) 2023 – the first post-pandemic crisis year.

We justify the exclusion of 1998 and 2008 from certain sub-periods due to the difficulty of classifying these years distinctly as pre-crisis or crisis periods within the context of the SNG sector. We recognized that in these instances, the economic conditions might not have reflected the onset or full impact of the crisis, thus complicating clear categorization.

The empirical research comprised two stages. In the first stage, we conducted correlation analysis using two-sided significance tests for Pearson correlation coefficients. We analyzed the interrelations

2 In the context of empirical analyses, we adopted the definition of the SNG subsector provided by the European System of National Accounts – ESA 2010 (European Commission 2013). This system facilitates the coordination of international macroeconomic accounts within EU member states and forms the basis for decision-making in the public finance sector. According to ESA 2010, in unitary states, the scope of SNG corresponds to that of local government, whereas in federal states, it encompasses two subsectors: state government and local government. This division enables detailed analysis and comparison of fiscal activities at various governmental levels.

between the size of the SNG sector, defined by the indicators presented in Table 3, and specific economic indicators (GDP per capita PPS (Purchasing Power Standards)), unemployment, and real GDP growth) in the countries studied. The analysis was performed both for the entire 1995–2023 period and the nine sub-periods described above. It should be acknowledged that correlation analysis has several limitations, including the possibility of omitted variable bias and the inability to identify causality. Consequently, these results should be treated as supporting evidence.

Table 3. Indicators describing the size of the SNG sector

Indicator Symbol	Description
Rev_GDP	SNG revenues as % of GDP
Rev_GG	SNG revenues as % of total revenues in the public finance sector (General Government, GG)
Exp_GDP	SNG expenditures as % of GDP
Exp_GG	SNG expenditures as % of total expenditures in the public finance sector (GG)
Comp_GDP	SNG employee compensations as % of GDP
Comp_GG	SNG employee compensations as % of total employee compensation expenditures in the public finance sector (GG)
Social_GDP	SNG social protection expenditures as % of GDP
Social_GG	SNG social protection expenditures as % of total social protection expenditures in the public finance sector (GG)
GFCF_GDP	SNG gross fixed capital formation as % of GDP
GFCF_GG	SNG gross fixed capital formation as % of total gross fixed capital formation expenditures in the public finance sector (GG)
Def_GDP	SNG deficit as % of GDP
DebtCH_GDP	Change in SNG debt as % of GDP
Debt_GDP	SNG debt as % of GDP
Debt_GG	SNG debt as % of total public sector debt in the public finance sector (GG)

Note: The consolidated data were used for measuring the total public finance sector size.

Source: own elaboration.

The fiscal indicators presented in Table 3 are employed to ensure a comprehensive and conceptually consistent measurement of the size and functional scope of the SNG sector in the analysed countries. The selection of these indicators is guided by three key considerations: (i) their theoretical relevance within the fiscal federalism literature, (ii) their empirical suitability for capturing both the scale and structural composition of SNG activity, and (iii) their cross-country comparability over a long time horizon.

Revenue and expenditure indicators expressed as a percentage of GDP (Rev_GDP, Exp_GDP) reflect the macroeconomic dimension of SNG activity, while the corresponding indicators measured as shares of the general government sector (Rev_GG, Exp_GG) enable an assessment of the vertical allocation of fiscal resources and competencies within the public finance system, and thus

of the degree of fiscal decentralization. In addition, indicators related to employee compensation and social protection expenditures (Comp_GDP, Comp_GG, Social_GDP, Social_GG) capture the functional composition of SNG spending, which is particularly relevant during crises.

Indicators of gross fixed capital formation (GFCF_GDP, GFCF_GG) reflect the investment capacity of SNGs, whereas deficit and debt measures (Def_GDP, DebtCH_GDP, Debt_GDP, Debt_GG) allow for an assessment of fiscal behavior and financial sustainability over the crisis cycle. The use of consolidated general government data ensures measurement consistency and avoids double counting within the public finance sector.

Taken together, the adopted set of indicators provides a multidimensional characterization of the SNG sector, encompassing its scale, structure, functional and investment activity, and fiscal sustainability. This makes the indicator framework particularly well suited for examining the adaptive responses of SNGs under conditions of multiple, overlapping crises.

The results of the correlation analysis provided initial insights and served as input for further empirical investigations in the subsequent phase. For this purpose, we employed cluster analysis, a statistical technique that categorizes objects based on their similarities. This method arranges observations into homogeneous groups such that those within the same cluster exhibit greater similarity to each other than to those in different clusters (Kaufman and Rousseeuw 2005; Everitt et al. 2011; Scitovski et al. 2021).

In our study, we applied the k-means method to classify countries based on specific similarities in the models of fiscal federalism they implemented. For cluster identification, we used the three most significant variables identified by the correlation analysis: SNG revenues, SNG expenditures, and SNG gross fixed capital formation. To capture the relative importance of SNG within the general government sector, we employed the Rev_GG indicator. Additionally, to assess the significance of SNG for the economy, we utilized the Exp_GDP and GFCF_GDP indicators.

The procedure for calculating clusters was as follows. First, we normalized the data for each variable Rev_GG, Exp_GDP and GFCF_GDP according to the formula:

$$\frac{x_i - \overline{x}}{\sigma}, \tag{1}$$

where x_i is the original value for the i-th observation of a given variable, $\overline{x}$ is the mean of all observations for a given variable and σ is the standard deviation for these observations. The normalized variables were denoted as Rev, Exp and GFCF, respectively.

Then we denoted each data point as $\mathbf{z}_i = (\text{Rev}_i, \text{Exp}_i, \text{GFCF}_i)$ for $i = 1, 2, \ldots, n$ (the set of data points consists of n observations for each variable: Rev, Exp, and GFCF), and the centroid for a cluster as $\mu_j = (\mu_{\text{Rev}_j}, \mu_{\text{Exp}_j}, \mu_{\text{GFCF}_j})$ for cluster j.

The Euclidean distance between a data point $\mathbf{z}_i$ and a centroid μ_j is given by:

$$\|\mathbf{z}_i - \mu_j\| = \sqrt{\left(\text{Rev}_i - \mu_{\text{Rev}_j}\right)^2 + \left(\text{Exp}_i - \mu_{\text{Exp}_j}\right)^2 + \left(\text{GFCF}_i - \mu_{\text{GFCF}_j}\right)^2}. \tag{2}$$

The objective function to minimize in k-means clustering, which is the within-cluster sum of squares (WCSS) – based on the Euclidean distance of data points from centroids, becomes:

$$\mathrm{WCSS} = \sum_{j=1}^{k} \sum_{\mathbf{z}_i \in C_j} \|\mathbf{z}_i - \mu_j\|^2, \tag{3}$$

where:
k – the number of clusters;
C_j – the set of points in cluster j;
μ_j – the centroid of cluster j;
$\|\mathbf{z}_i - \mu_j\|$– the Euclidean distance between a point z_i and the centroid μ_j.

The k-means clustering procedure starts with random initialization of k centroids in the 3-dimensional space defined by Rev, Exp, and GFCF. Then, each data point $\mathbf{z}_i$ is assigned to the nearest centroid μ_j based on the Euclidean distance formula above. In the next step, the centroids are recalculated by taking the mean of all data points assigned to each cluster. For cluster j, the new centroid μ_j is calculated as, respectively:

$$\mu_{\mathrm{Rev}_j} = \frac{1}{|C_j|} \sum_{\mathbf{z}_i \in C_j} \mathrm{Rev}_i; \quad \mu_{\mathrm{Exp}_j} = \frac{1}{|C_j|} \sum_{\mathbf{z}_i \in C_j} \mathrm{Exp}_i; \quad \mu_{\mathrm{GFCF}_j} = \frac{1}{|C_j|} \sum_{\mathbf{z}_i \in C_j} \mathrm{GFCF}_i, \tag{4}$$

where $|C_j|$is the number of points in cluster j.

This procedure is iterated until the centroids no longer change significantly.

As the study period for this research spanned almost three decades a duration sufficient to witness systemic shifts in individual countries the clustering procedures were conducted separately for two sub-periods: (A) 1995–2007 and (B) 2009–2023. Despite these divisions, they revealed similar characteristics of distinctive models of fiscal federalism for both sub-periods, as presented in the Results & Discussion section.

The correlation analysis revealed noteworthy relationships between SNG size and the macroeconomic performance of EU countries. Statistically significant correlations were observed between indicators such as a country's wealth and the size of its SNG sector (measured relative to GDP) or its share in total public finance sector. The strongest associations with macroeconomic variables occurred with variables describing SNG revenue, expenditure, and gross fixed capital formation. These findings are presented in Table 3. Notably, excluding 1998 and 2008 does not significantly impact the primary correlation patterns. The correlation results for these two years are provided in the appendix.

Based on the relationships outlined in Table 4, the following observations can be made:

- A long-term positive relationship exists between the size of SNG and the degree of fiscal decentralization, and national wealth measured as GDP per capita in PPS. This is a relatively strong relationship (correlation coefficients approximately 0.3), given the large number of factors that influence GDP.
- A long-term beneficial relationship is evident between SNG size and fiscal decentralization, and the unemployment rate; specifically, a larger SNG sector is negatively correlated with high unemployment. The strength of this relationship is weaker than that between SNG size and GDP.

- Real economic growth rates are slightly negatively correlated with the size of the SNG sector. In the context of the positive relationships mentioned above, this suggests not so much a counter-growth character of large SNGs, but rather their counter-cyclical profile. Namely, an increase in SNG activity is used as a policy instrument to stimulate growth during economic downturns, while SNG resources are relatively reduced during periods of economic prosperity.

Table 4. Correlations for the entire study period

		Rev_GDP	Rev_GG	Exp_GDP	Exp_GG	Comp_ GDP	Comp_GG	Social_ GDP	Social_GG	GFCF_ GDP	GFCF_GG	Def_GDP	DebtCh_ GDP	Debt_ GDP	Debt_GG
GDP per capita PPS	Correlation coef.	.335**	.256**	.334**	.309**	.281**	.267**	.313**	.285**	.176**	.263**	− 0.053	.183**	.428**	.312**
	Significance	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.000	0.428	0.009	0.000	0.000
	No. of obs.	225	225	225	225	225	225	225	225	225	225	225	200	206	205
GDP real change	Correlation coef.	− 0.124	− 0.100	-.137*	− 0.054	− 0.098	− 0.074	− 0.101	− 0.053	− 0.130	− 0.068	.202**	-.184**	-.197**	− 0.042
	Significance	0.063	0.136	0.040	0.418	0.145	0.272	0.129	0.425	0.051	0.309	0.002	0.009	0.004	0.550
	No. of obs.	225	225	225	225	225	225	225	225	225	225	225	200	206	205
Unemp-loyment	Correlation coef.	-.210**	− 0.131	-.196**	-.194**	-.181**	-.201**	-.185**	-.172*	-.169*	− 0.103	-.154*	0.097	− 0.071	− 0.134
	Significance	0.002	0.053	0.004	0.004	0.007	0.003	0.006	0.010	0.012	0.128	0.022	0.172	0.313	0.056
	No. of obs.	220	220	220	220	220	220	220	220	220	220	220	198	205	204

Notes: All shaded cells with correlation coefficients depict the results with at least 0.10 significance level (two-sided).

Additionally: * depicts 0.05 significance level (two-sided). ** depicts 0.01 significance level (two-sided).

Definitions of variables are presented in Table 2.

Source: own elaboration.

The next stage of the analysis verified whether the analysis results were stable over time. Based on the results presented in Table 5, the following conclusions can be drawn:

- Among the analyzed macroeconomic variables, the positive relationship between GDP per capita PPS and the size of the SNG remains the most stable over time.
- During the financial crisis of 1998, a large SNG sector appears to have played a significant role in helping economies restore equilibrium. This observation suggests that robust local government structures may have been crucial in implementing effective fiscal measures and providing necessary public services that mitigated the crisis's impact. The ability of these governments to act decisively may have been a key factor in stabilizing their economies more quickly than those with less developed local governmental frameworks.
- Similarly, although with less pronounced effectiveness, the presence of a substantial SNG sector might have also mitigated the impacts of the 2008 financial crisis. While the correlation is not as strong as in 1998, the data still suggest that well-resourced local governments likely contributed to economic resilience. This pattern underscores the potential of local governments to absorb economic shocks, although the degree of impact can vary depending on the specific nature and severity of each crisis.
- During the COVID-19 pandemic, a notable weakening in the relationship between national wealth and SNG sector size was observed. This shift suggests that the unconventional challenges posed by the pandemic, such as the urgent need for healthcare services, economic support measures, and crisis management at the local level, might have fundamentally altered the traditional dynamics between economic prosperity and local governmental capacity. Wealthy nations, typically characterized by more extensive local government structures, may have found that these structures were less effective in responding swiftly to the unique demands of the pandemic. This observation indicates a need to reassess how resources are allocated and managed within local governments, potentially driving a shift toward more flexible, adaptive, and resilient local governance frameworks that are better equipped to respond to sudden and severe societal challenges.

Table 5. Summary of correlation results (correlation coefficients only) for sub-periods

	Rev _GDP	Rev _GG	Exp _GDP	Exp _GG	Comp _GDP	Comp _GG	Social _GDP	Social _GG	GFCF _GDP	GFCF _GG	Def _GDP	DebtCh _GDP	Debt _GDP	Debt _GG
1995–1997														
GDPpc_PPS	.703**	.626**	.699**	.634**	.634**	.597**	.475*	.438*	.593**	.537**	0.081	0.212	0.728	.888*
GDP_change	− 0.033	− 0.066	− 0.036	− 0.005	0.011	− 0.146	− 0.075	− 0.039	0.195	0.051	0.020	− 0.032	− 0.374	− 0.362
Unempl.	− 0.212	− 0.058	− 0.206	− 0.106	− 0.196	− 0.164	− 0.252	− 0.204	0.050	0.085	− 0.075	.795**	0.260	0.634
1999–2000														
GDPpc_PPS	.645**	.559**	.639**	.632**	.557**	.598**	.438*	.419*	.582**	.563**	0.111	− 0.335	.624**	0.363
GDP_real_ch	0.244	0.347	0.241	0.390	0.201	0.288	0.078	0.158	.641**	.587**	0.046	− 0.226	0.086	0.173
Unempl.	-.406*	− 0.327	− 0.395	− 0.380	− 0.335	− 0.361	− 0.319	− 0.307	− 0.359	− 0.351	− 0.272	0.519	− 0.296	− 0.178
2001–2004														
GDPpc_PPS	.596**	.492*	.603**	.553**	.514**	.509**	.441*	.422*	.572**	.590**	− 0.291	0.339	.599**	0.310
GDP_real_ch	-.534**	− 0.374	-.544**	− 0.375	− 0.385	− 0.357	-.425*	− 0.319	-.431*	-.503*	0.334	− 0.364	-.621**	− 0.145
Unempl.	− 0.385	− 0.298	− 0.388	− 0.341	− 0.332	− 0.297	− 0.323	− 0.325	-.421*	− 0.314	0.173	− 0.213	− 0.289	− 0.184
2005–2007														
GDPpc_PPS	.451*	0.303	.447*	0.386	0.395	0.340	0.373	0.334	0.192	.509**	0.080	0.102	.535**	0.141
GDP_real_ch	-.442*	− 0.307	-.443*	− 0.298	− 0.316	− 0.220	-.414*	− 0.351	− 0.113	-.484*	0.094	− 0.022	-.495*	0.218
Unempl.	− 0.191	− 0.096	− 0.193	− 0.198	− 0.201	− 0.083	− 0.263	− 0.288	− 0.070	− 0.062	0.089	− 0.190	− 0.038	− 0.207

	Rev _GDP	Rev _GG	Exp _GDP	Exp _GG	Comp _GDP	Comp _GG	Social _GDP	Social _GG	GFCF _GDP	GFCF _GG	Def _GDP	DebtCh _GDP	Debt _GDP	Debt _GG
2009–2010														
GDPpc_PPS	.492*	0.320	.486*	.415*	.442*	0.393	.420*	0.384	– 0.083	0.346	– 0.085	0.376	.539**	0.282
GDP_real_ch	0.248	0.180	0.254	0.235	0.168	0.226	0.180	0.149	– 0.013	0.259	– 0.146	0.287	0.265	– 0.078
Unempl.	– 0.272	– 0.066	– 0.238	– 0.185	– 0.198	– 0.209	– 0.234	– 0.194	0.311	0.007	– 0.274	– 0.068	– 0.217	0.038
2011–2015														
GDPpc_PPS	.471*	0.332	.476*	.419*	.475*	.403*	.412*	0.379	– 0.137	0.250	– 0.264	0.323	.523**	.529**
GDP_real_ch	– 0.147	– 0.068	– 0.144	– 0.047	– 0.110	– 0.035	– 0.120	– 0.079	0.132	– 0.082	0.024	– 0.117	– 0.129	0.110
Unempl.	– 0.359	– 0.265	– 0.332	– 0.345	– 0.329	– 0.384	– 0.217	– 0.200	-.424*	– 0.280	– 0.212	0.180	– 0.155	– 0.390
2016–2019														
GDPpc_PPS	0.369	0.278	0.375	0.323	0.305	0.260	0.383	0.356	0.156	0.188	– 0.245	0.314	.429*	.421*
GDP_real_ch	-.486*	– 0.365	-.485*	– 0.386	-.426*	-.396*	– 0.337	– 0.261	– 0.294	– 0.356	0.129	– 0.260	-.554**	– 0.383
Unempl.	– 0.148	– 0.129	– 0.146	– 0.170	– 0.155	– 0.205	– 0.101	– 0.101	– 0.330	– 0.045	0.000	– 0.001	0.079	– 0.205
2020–2022														
GDPpc_PPS	0.209	0.140	0.214	0.229	0.147	0.140	0.294	0.298	– 0.095	0.045	– 0.139	0.282	0.295	.430*
GDP_real_ch	– 0.383	– 0.358	– 0.378	– 0.320	– 0.392	-.420*	– 0.123	– 0.051	-.471*	– 0.391	0.010	– 0.126	– 0.365	– 0.285
Unempl.	0.002	0.010	0.012	– 0.034	0.017	– 0.065	– 0.046	– 0.056	– 0.083	0.121	– 0.197	0.013	0.206	– 0.036

	Rev _GDP	Rev _GG	Exp _GDP	Exp _GG	Comp _GDP	Comp _GG	Social _GDP	Social _GG	GFCF _GDP	GFCF _GG	Def _GDP	DebtCh _GDP	Debt _GDP	Debt _GG
2023														
GDPpc_PPS	0.182	0.109	0.190	0.215	0.121	0.111	0.292	0.288	− 0.254	0.084	− 0.197	0.301	0.323	.406*
GDP_real_ch	0.158	0.170	0.139	0.145	0.159	0.124	0.141	0.144	0.296	0.253	0.220	− 0.190	0.056	− 0.077
Unempl.	0.067	0.075	0.082	0.056	0.078	− 0.004	0.020	0.019	0.045	0.189	− 0.258	0.088	0.232	0.038

Notes: All shaded cells depict the results with at least 0.10 significance level (two-sided).

Additionally: * depicts 0.05 significance level (two-sided). ** depicts 0.01 significance level (two-sided).

Number of observations (for correlations between each pair of variables) amounts to 25 for each period with the exception of 1995–1997 when it varies from 4 to 25. Limited number of observations (from 4 to 12) is for variables DebtCh_GDP, Debt_GDP and Debt_GG in this period. Definitions of variables are presented in Table 2.

Source: own elaboration.

These evolving patterns of the relationship between the economy and SNGs prompt a search for the most growth-promoting models of fiscal federalism. At the same time, the impact of SNG sector on the economy may not be uniform across different countries. Its strength may derive from the diverse national models of federalism. Therefore, we conducted a cluster analysis using the k-means method.

This analysis identified three distinctive models of the SNG sector's role in the economy. These models remained stable over time despite the clustering being performed separately for 1995–2007 (period A) and 2009–2023 (period B). The methodology for this division is described in the Data and Methodology section, while detailed information about the estimations (ANOVA results, elbow curves) is presented in the appendices. The clusters exhibit the following characteristics (see also Table 6):

- Cluster 1: SNGs with high revenues and expenditures but moderate investments: this represents the "redistributive model".
- Cluster 2: A relatively small SNG sector across all criteria: this represents the "minimalist model".
- Cluster 3: SNGs where revenues and expenditure are relatively moderate, yet investments made by the SNG are disproportionately high: this represents the "pro-investment decentralization model".

Table 6. Summary of cluster characteristics

	(A) 1995–2007			(B) 2009–2023		
	Cluster 1	Cluster 2	Cluster 3	Cluster 1	Cluster 2	Cluster 3
Rev_GG	1.435	– 0.933	– 0.025	1.489	– 0.967	– 0.193
Exp_GDP	1.499	– 0.914	– 0.066	1.508	– 0.957	– 0.209
GFCF_GDP	0.302	– 1.053	0.548	0.479	– 1.164	0.413
No. of observations	21	31	48	30	34	61
Missing observations	0	0	0	0	0	0

Source: own elaboration.

The three cluster profiles are similar for both sub-periods. However, this does not mean that a country will always be assigned to the same cluster. On the contrary, over the years and with the evolution of their fiscal federalism models, some countries have changed their cluster assignments. This can be observed in Figures 2 and 3. These charts also illustrate how individual countries have evolved within the respective clusters with regard to their GDP per capita PPS. In the appendix, the following supplementary figures are presented for periods A and B:

- GDP per capita PPS vs. SNG GFCF as a percentage of GDP,
- Real GDP change vs. SNG revenues as a percentage of GDP,
- Unemployment rate vs. SNG revenues as a percentage of GDP.

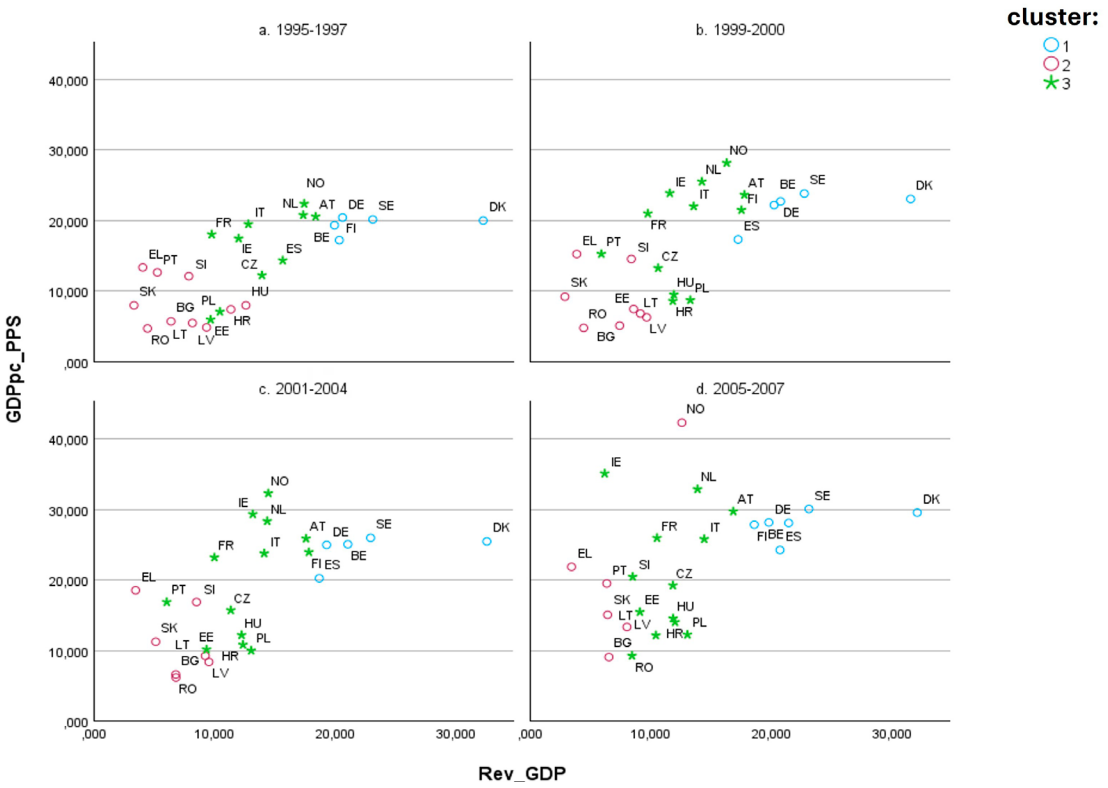

Figure 2. Evolution of GDP per capita PPS vs. SNG revenues as % of GDP, clustered, 1995–2007
Source: own elaboration.

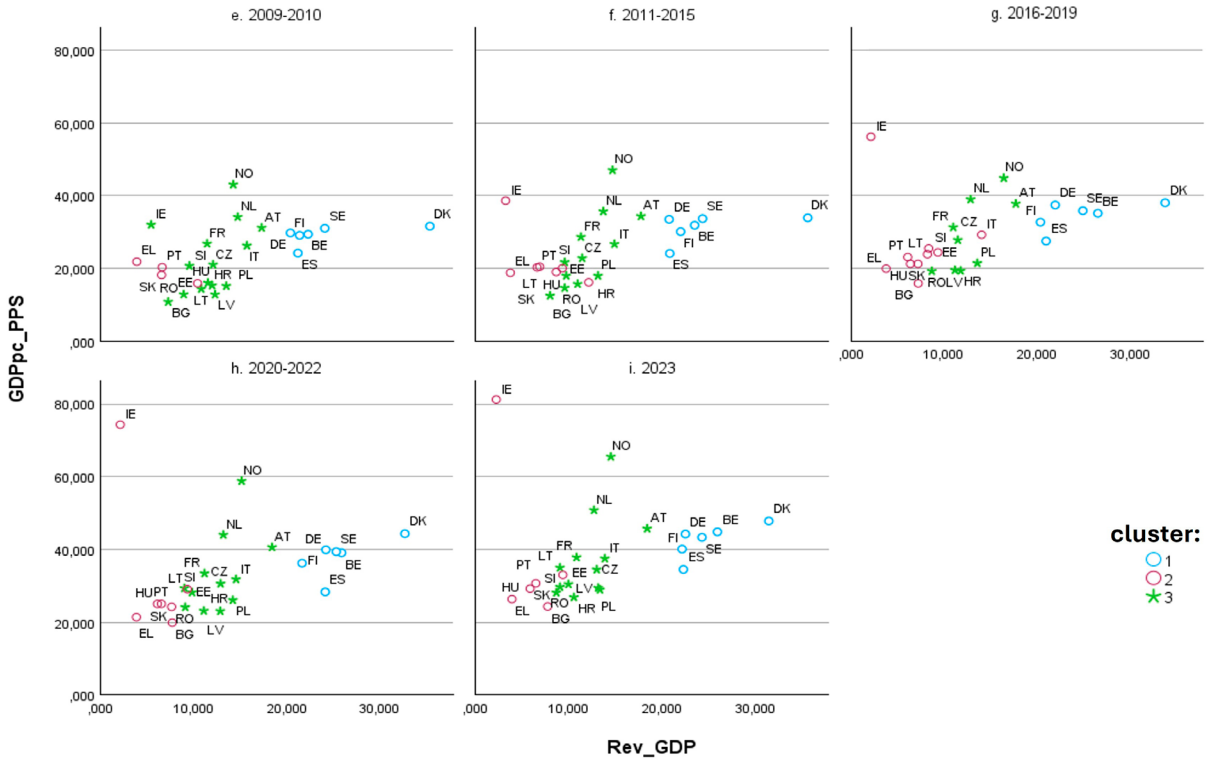

Figure 3. Evolution of GDP per capita PPS vs. SNG revenues as % of GDP, clustered, 2009–2023
Source: own elaboration.

Grouping countries enabled a comparison of their economic performance based on the SNG clusters they belong to. The results of this analysis are presented for countries that did not change their cluster assignment in the sub-periods. This allows for the calculation of comparable average values to assess how these economies performed in terms of GDP per capita PPS, real GDP change, and unemployment rate, in relation to the SNG model of their respective cluster. A summary of these calculations is provided in Table 7, and the findings are reviewed in the Discussion section.

Table 7. Economic performance comparison of various clusters

		GDP pc PPS; thsd.	Real GDP change; %	Unemployment; %		GDP pc PPS; thsd.	Real GDP change; %	Unemployment; %
	1995–2007:				2009–2023:			
Cluster 1	1995–1997	20.05	2.76	9.28	2009–2010	29.57	– 1.20	8,33
	1999–2000	22.86	3.49	7.10	2011–2015	32.66	1.18	8,04
	2001–2004	25.27	1.51	6.61	2016–2019	35.50	2.13	6,74
	2005–2007	28.86	2.70	7.52	2020–2022	39.24	1.22	6,65
					2023	43.80	0.51	6,35
CAGR for GDPpc PPS; median GDP change and Unemployment:		**+12.91%**	**2.6%**	**7.7%**		**+10.32%**	**1.2%**	**7.3%**
Cluster 2	1995–1997	6.83	4.15	12.20	2009–2010	21.09	– 2.80	11,63
	1999–2000	8.00	0.66	16.15	2011–2015	19.54	– 2.43	19,72
	2001–2004	10.27	5.24	14.84	2016–2019	21.53	2.10	14,73
	2005–2007	14.21	7.79	8.90	2020–2022	23.23	1.59	10,80
					2023	28.53	2.43	8,80
CAGR for GDPpc PPS; median GDP change and Unemployment:		**+27.64%**	**4.8%**	**13.1%**		**+7.86%**	**1.4%**	**11.6%**
Cluster 3	1995–1997	18.02	2.18	11.20	2009–2010	23.91	– 0.97	7,85
	1999–2000	22.00	3.77	8.80	2011–2015	25.73	1.69	8,11
	2001–2004	23.78	1.70	7.90	2016–2019	29.54	2.59	5,58
	2005–2007	25.96	3.15	6.80	2020–2022	32.02	1.82	4,93
					2023	36.16	0.31	4,35
CAGR for GDPpc PPS; median GDP change and Unemployment:		**+12.95%**	**3.1%**	**7.4%**		**+10.89%**	**1.5%**	**5.7%**

Note: Cluster compositions for 1995–2007: Cluster 1: BE, DK, DE, SE; Cluster 2: BG, EL, LT, SK; Cluster 3: CZ, IE, FR, IT, NL, AT, PL. Cluster compositions for 2009–2023: Cluster 1: BE, DK, DE, ES, FI, SE; Cluster 2: EL, PT; Cluster 3: CZ, FR, LV, NL, AT, PL, RO, NO.

Source: own elaboration.

Discussion

While the empirical analysis relies on relatively parsimonious methods namely correlation analysis and k-means clustering the results gain analytical depth when interpreted in light of institutional heterogeneity, crisis-specific contexts, and country-level fiscal practices. In this sense, the adopted methodological approach should be understood as exploratory rather than causal, aimed at identifying stable empirical regularities and meaningful patterns across different models of fiscal federalism. The cluster-based framework enables a comparative interpretation of how structurally distinct SNG models translate into divergent macroeconomic outcomes, particularly during periods of economic stress.

Importantly, the observed differences between clusters do not merely represent statistical artifacts but reflect underlying institutional configurations, policy priorities, and fiscal capacities of SNGs. For example, the superior performance of the pro-investment decentralization model (Cluster 3) during both crisis and post-crisis periods can be interpreted as evidence of the countercyclical role of subnational public investment, which tends to be more flexible and territorially targeted than central-level interventions. Conversely, the weaker performance of the minimalist model (Cluster 2) highlights the limited shock-absorbing capacity of under-resourced SNG sectors, particularly in the face of large-scale economic disruptions.

By embedding the quantitative findings within this broader institutional and crisis-oriented perspective, the Discussion mitigates the inherent limitations of simple correlation-based methods and enhances the robustness and interpretability of the results. This interpretative layer is particularly relevant in the context of multiple, overlapping crises, where the structural characteristics and policy orientation of fiscal decentralization models may matter as much as, or more than, their sheer size. Nevertheless, it is important to point out that the variables used in the clustering are significantly correlated, particularly in the case of revenues and expenditure, with a correlation coefficient of approximately 0.9. The correlation coefficients are lower with respect to investment and revenues or expenditures, ranging from 0.3 to 0.4. Although we normalized the data to mitigate this problem, such a data profile still suggests that these results should be used to identify general patterns rather than for strict modeling applications. Therefore, the investment component should be treated as the primary differentiating factor.

The analysis allowed us to identify a broad nexus between SNG models and economic stability and growth. Findings for the period 1995–2007 include the following:

- The comparison between Cluster 1 and Cluster 3 reveals that Cluster 3 (“pro-investment decentralization model”), with its stronger investment focus and lesser involvement in redistribution and routine tasks, performs slightly better across all economic parameters.
- Cluster 2 (“minimalist model”) experienced the fastest GDP per capita PPS growth. However, it also had significantly higher unemployment. This cluster, which solely comprises developing countries, was notably poorer than others and exhibited a faster real convergence due to macroeconomic factors. Yet, this cluster experienced the most severe negative impacts during the 1998 financial crisis.

Findings for the period 2009–2023 include the following:

- The comparison between Cluster 1 and Cluster 3 for this period shows that Cluster 3 ("pro-investment decentralization model"), which maintains a strong investment character and reduced role in redistribution, social policy implementation, and current tasks, consistently outperformed in all economic parameters.
- Cluster 2 ("minimalist model") recorded the poorest economic performance overall and was most adversely affected by the 2008–2009 global financial crisis, confirming our hypothesis that a larger SNG sector provides a stabilizing influence on the economy.

These findings align with the results of numerous scholarly works that explore the positive impact of public investments, including those by local government units, on economic growth and resilience to external economic shocks (Jarosiński 2023; Danaj and Reçi 2024; Matić 2024). Our results confirm the important value of the investment activities of local authorities. In a similar context, namely foreign direct investments, this positive relationship is also demonstrated by Rodríguez-Pose and Ganau's (2025) study of 159 regions across all EU countries.

The results presented in this study indicating that Cluster 1 and Cluster 3 have significantly higher economic growth are also consistent with Rodríguez-Pose and Muštra (2022), who show that regional GDP per capita growth in PPS is positively correlated (lagged relationship) with the degree of decentralization at the micro level. Rodríguez-Pose and Muštra further demonstrate that the quality of governance is also an important pro-growth factor.

To some extent, our findings diverge from those of Lago-Peñas, Martínez-Vazquez, and Sacchi (2020), who studied the exposure of EU countries to the exogenous macroeconomic shocks and the subsequent economic responses from 1995 to 2014. Their study demonstrated that more decentralized countries performed better in terms of fiscal balances and fiscal policies during and after crisis periods. While this is a strong argument for decentralized fiscal systems, it does not align with our findings, which show the superior macroeconomic performance of countries that are not only decentralized but also have a strong investment focus on SNG policies. This SNG profile typically translates into larger budget deficits, especially when investment is used as a countercyclical instrument.

To place these empirical findings within the broader evolution of the literature, the discussion draws on recent contributions that conceptualize fiscal federalism as an adaptive system operating under conditions of sequential and overlapping crises, as summarised in Table 1. The interpretation of the clustering results can thus be further strengthened by referring to recent studies that frame fiscal federalism not as a static institutional arrangement, but as a system whose performance depends on its capacity to adapt to compound and recurrent shocks. Rather than repeating the detailed literature discussion presented in the review section, this discussion selectively uses the studies synthesized in Table 1 as an interpretative framework for the empirical findings. These contributions consistently indicate that the effectiveness of fiscal federalism amid crisis conditions depends less on the aggregate degree of decentralization and more on institutional design, coordination mechanisms, and the functional orientation of SNG activity (Brosio 2024; Dougherty, Montes Nebreda, and Urrutia 2025; Herrero-Alcalde, Martín-Román, and Moral-Arce 2025; Martínez-Vazquez 2025; Shrestha and Hankla 2025; Shafi and Mallinson 2026).

From this perspective, the stronger performance observed in Clusters 1 and 3 can be interpreted as evidence that decentralization supports macroeconomic stability and economic growth primarily when embedded in mature institutional environments and backed by sufficient fiscal capacity at the subnational level. This interpretation is consistent with arguments emphasizing that decentralised systems are not inherently stabilizing, but become so only when they combine investment capacity, effective intergovernmental coordination, and credible fiscal frameworks (Brosio 2024; Martínez-Vazquez 2025). By contrast, the weak performance of the minimalist decentralization model (Cluster 2) highlights the limited shock-absorbing capacity of an under-resourced SNG sector, particularly in countries at lower levels of economic development, where decentralization may increase vulnerability to external shocks rather than mitigate it (Shrestha and Hankla 2025).

The results also allow for policy-relevant conclusions. First, fiscal decentralization remains a viable and appropriate institutional arrangement for developed and highly developed economies, including current EU member states, provided that it is accompanied by effective coordination and fiscal risk-sharing mechanisms. The experience of Clusters 1 and 3 suggests that decentralization can enhance economic resilience amid polycrisis, whereas poorly designed or fiscally constrained decentralization frameworks fail to deliver stabilizing effects.

Second, the findings underscore the importance of shifting investment-related decision-making and implementation to the subnational level. While many redistributive and stabilization policies can increasingly be administered centrally, supported by technological progress and integrated fiscal systems, the identification of investment needs, project selection, and oversight appear more effective at the local and regional level. SNGs are better positioned to tailor investment strategies to territorial characteristics and to respond countercyclically to asymmetric shocks, as evidenced by the strong performance of the pro-investment decentralization model (Cluster 3). From a policy perspective, this suggests that strengthening the investment capacity of SNGs, rather than expanding their redistributive functions, constitutes a key channel through which fiscal federalism can enhance system resilience in the current era of polycrisis, particularly within the EU's multilevel governance framework.

Finally, it should be acknowledged that this study has several limitations that should be taken into account when interpreting the results. From a methodological perspective, the analysis relies on correlation analysis and k-means clustering, which are exploratory tools and do not allow for causal inference. While suitable for identifying stable associations and structural patterns across countries, the results should therefore be interpreted with caution. In addition, data availability and cross-country comparability impose constraints on the analysis. Although the use of consolidated general government data ensures internal consistency, it may conceal important within-country institutional heterogeneity of SNGs. Finally, cross-country comparisons necessarily abstract from legal, political, and institutional differences shaping fiscal decentralization in practice. Despite these limitations, the adopted framework provides a coherent basis for comparative analysis and offers meaningful insights into the role of SNGs amid multiple, overlapping crises.

Conclusions

The analysis of the theoretical frameworks of fiscal federalism, combined with an empirical examination of EU countries, enabled the identification of three distinct models that reflect the diverse roles of subnational governments (SNGs) in the economy, especially within the context of crisis-driven challenges and the consequent shifts in SNG financing. Cluster 1, which features SNGs with significant revenues and expenditures but lower local government investments, is termed the "redistributive model." A key aspect of this model is the prioritization of stable local government current policies, even at the cost of reduced developmental investment. Cluster 2, characterized by relatively small SNGs in all aspects, is defined as the "minimalist model." Meanwhile, Cluster 3, with SNGs that have moderate revenues and expenditures but comparatively high local government investments, is termed the "pro-investment decentralization model."

Interestingly, although a general correlation was found whereby a larger SNG sector is positively associated with GDP per capita in PPS terms, the analysis at the level of individual models revealed variations in this relationship. Cluster 2, which features a small SNG sector, consistently exhibited considerably weaker results during the crisis periods and over the entire 2009–2023 period. In contrast, over the longer term, Cluster 3 ("pro-investment decentralization model"), characterized by its focus on investments and a moderate role in redistribution and operational tasks, emerged as the most developmentally favorable. Importantly, the cluster profiles remained consistent across both sub-periods, and most countries retained stable cluster assignments throughout these two more than decade-long sub-periods. The minor changes in cluster composition, due to a few countries migrating between clusters, indicate an evolution rather than a revolution in financial and adaptive strategies in response to shifting economic conditions and crises.

A blurring of previously distinct differences between clusters occurred in the final year of the analysis, 2023. This phenomenon can be interpreted in several ways. First, a one-year period is too brief to adequately assess enduring changes and their impact on the public sector of various countries. Second, the differences might be attributed to the varied impacts of the war in Ukraine on individual EU countries and their differing economic resilience to external shocks. Third, these observations could indicate a paradigm shift in public financial management, involving a reassessment of priorities and strategies in response to escalating geopolitical risks. These findings highlight the need for future comprehensive scientific research. Understanding and identifying these factors will be essential for forecasting future trends in SNG model changes and predicting responses to similar crises.

The cluster analysis results confirmed the diversity of public financial management models across various EU countries and the differential impacts of external economic shocks on the unique fiscal profiles of SNG sectors. The results also demonstrated that the "pro-investment decentralization model" exhibits the highest efficiency among the analyzed models. This may stem from a more precise analysis of needs at the local level, as opposed to the central level, which, in combination with improved oversight of investment projects, enhances the effectiveness of public policy and bolsters crisis adaptation capabilities.

In summary, the findings indicate that completely remodeling or radically changing the theoretical foundations of fiscal federalism is unnecessary. Instead, it is advisable to progressively adjust existing theoretical assumptions and principles to align with current realities, thereby more effectively addressing the dynamically changing needs of both central and local governments during an era of multiple crises. The concept of fiscal federalism should remain a fundamental reference in designing fiscal relationship systems across various countries, providing a robust framework for financial stability and responsible public management. Furthermore, it should enhance adaptability and flexibility in resource management, which is essential for rapid responses to local challenges. The incorporation of modern data management tools and economic analysis can further bolster the forecasting and operational capabilities at various levels of public administration, improving the prediction of fiscal decision impacts and the adaptation of policies to rapidly evolving economic and social conditions. Our research underscores the critical role of adaptability and flexibility in models of fiscal federalism, which are responsive to the dynamically changing economic and social conditions in EU countries. Transforming these models towards more investment-oriented and locally focused approaches may lead to better crisis management and long-term economic development.

Finally, the exploratory nature of the empirical approach adopted in this study points to several promising directions for further research. Future studies could extend the present analysis by applying more advanced empirical methods, such as panel data models, to control for unobserved heterogeneity and dynamic effects over time. Moreover, crisis-focused causal designs, including difference-in-differences or event-study approaches, could be employed to more precisely identify the impact of specific crisis episodes on SNG behavior and macroeconomic outcomes. Such extensions would help deepen the understanding of causal mechanisms underlying the relationships identified in this study and further strengthen research on fiscal federalism amid multiple, overlapping crises.

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Comparative Economic Research. Central and Eastern Europe
Volume 29 Number 3, 2026
https://doi.org/10.18778/1508-2008.29.20

The Competitiveness of Turkish Foreign Trade in Selected Agri-Food Products Compared to Other Candidate Countries

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Abstract

This study evaluates the competitiveness of Türkiye's agri-food foreign trade relative to other European Union (EU) candidate countries (CCs). It explores trade volumes to examine Türkiye's position within the EU market. Competitiveness indicators show that the Turkish agri-food sector is well positioned to become a competitive player in the EU market, especially among the largest group of CCs covered by this analysis, with a high degree of specialization in fruit and vegetable exports. The analysis identifies Türkiye as a significant player due to its extensive agricultural land and diverse climate. However, challenges such as infrastructural gaps and inconsistent policies limit its full potential. Targeted policy reforms and investments in infrastructure and technology are essential to further enhance Türkiye's competitiveness.

Keywords: Türkiye, EU candidate countries, competitiveness, foreign trade, trade competitiveness indicators
JEL: F15, Q17

Funding information: Poznan University of Life Sciences, Poznan, Poland
Conflicts of interests: None.
Ethical considerations: The Author assures of no violations of publication ethics and takes full responsibility for the content of the publication.
Received: 18.12.2025. Verified: 22.01.2026. Accepted: 24.06.2026

Introduction

In today's uncertain times, increasing economic competitiveness, including foreign trade, especially in the European Union market, is crucial. A country's ability to compete effectively in the global marketplace is called international competitiveness, and it includes factors such as investment, economic growth, and trade advantages. The concept of national competitiveness can be understood as a nation's ability to generate the necessary resources to satisfy its domestic demands, as outlined in the Aldington Report (1985). This aligns with Scott and Lodge's (1985) definition of national competitiveness as a country's capability to create, produce, distribute, and service products in international trade while achieving increasing returns on its resources (Buckley, Pass, and Prescott 1988:177). The primary limitation of competition policy is that it is designed to resolve challenges within national borders. In essence, competition policy deals with internal competition within a country, while trade policy manages competition in international commercial relations (Sabır 2014:23).

Adam Smith's concept of absolute advantage (cheaper production) was one of the first abstractions, followed by Ricardo's concept of comparative advantage (price and cost differences), and the term was then fine-tuned by Heckscher and Ohlin based on efficiency (Maneschi 1992; Ingham 2004; Koo and Kennedy 2005; Sawyer and Sprinkle 2015). According to the Heckscher–Ohlin (H–O) theory, the volume and structure of international trade derive from differences in the real cost of production following from differences in extreme productivity of both factors. Differences in productivity are due to the relative abundance of factors in the respective countries (Helpman 2011:11; Krugman, Obstfeld, and Melitz 2018:37).

Two neo-factor theories extend the classical theory of resource abundance by incorporating a larger number of production factors; for instance, Vanek's three-factor theory identifies natural resources as a production factor that includes a country's agricultural land resources (Helpman 2011:12). Tesch (1980) further develops this factor-based approach through the theory of competitive advantage, which stems from the available products and production factors. This framework links competitiveness to various absolute and permanent production capabilities that follow from natural conditions such as land quality or climate and to relative and interim capabilities related to differences in the level of technical knowledge, human resource qualifications, and capital resources (Misala 2011). Balassa (1965:99) provided both the theoretical background for and empirical verification of comparative advantages.

Various authors have characterized competitiveness as a theoretical, multidimensional, and relative concept tied to the market mechanism. In analyzing its definitions, the concept can encompass different levels of aggregation, such as supranational, national, regional, local, industrial, sectoral, and even down to individual companies or farms. Collectively, these levels constitute the entities through which competitiveness can be analyzed (Siudek and Zawojska 2014:94).

The drivers of competitiveness differ across countries and can be categorized into two main areas: macroeconomic and microeconomic factors. Macroeconomic competitiveness is influenced by various institutions, policies, and public investments that shape the overall economic environment. Social infrastructure including education, healthcare, and public safety along with political

institutions, establishes the overarching framework for productive economic activities. Microeconomic factors are those that directly influence company productivity and labor force mobilization and include factor endowments and demand conditions. The literature on regional competitiveness identifies three groups of key factors that determine the international competitive status of a region – infrastructure and accessibility, human assets, and industrial environment – which, in turn, comprise several constituent sub-factors. Sub-factors under infrastructure and accessibility include basic, technological, and knowledge-based infrastructure, as well as habitat quality. Human assets include demographic trends and a highly skilled labor force. The industrial environment includes factors such as entrepreneurial culture, sectoral concentration, internationalization, specialization, innovation, nature and pattern of competition, the sufficiency of manufacturing resources, and government and institutional capability (Brykova 2007:12; Mizik 2021:2).

Measuring competitiveness involves evaluating and quantifying various factors that contribute to the ability of individuals, firms, industries, or countries to compete effectively. Furthermore, various methods are employed to measure this competitiveness. The Global Competitiveness Index (GCI) is a comprehensive assessment of national competitiveness that combines various indicators across different dimensions. It ranks countries based on their competitiveness and provides insights into their strengths and areas for improvement. Although the GCI is one of the most recognized composite indicators of national competitiveness in the literature, it has faced criticism for its instability, potential correlations, or reverse causality between its pillars, and the lack of a strong theoretical foundation (Petrylė 2017:30).

Other measures include trade indicators, which measure a country's competitiveness in international trade, such as the trade balance, trade openness, export diversification, export sophistication, and revealed comparative advantage. These indicators reflect a country's ability to compete in global markets (Gault and Soete 2022:1).

Regarding the limitations of the study, and because of the approach used and its international scope, this study does not account for a number of major aspects of foreign trade, such as historical or institutional variations at the country level. Extending the analysis to examine the above-mentioned issues will form the basis for further research.

In view of the above, this study examines the agri-food trade competitiveness of Türkiye relative to that of EU candidate countries (CCs) important partners within the European market based on available 2012–2022 EUROSTAT and FAOSTAT data. To achieve the stated research objective, the following research questions were posed:

RQ1: Is Türkiye's foreign trade in agri-food products competitive in the EU market?

RQ2: What is the competitiveness of Türkiye's agri-food trade compared to that of other EU CCs?

The study of foreign trade competitiveness is an important element in testing economic theories in the field of competitiveness research, and it shows which CCs, apart from Türkiye, may become competitive in the future in the EU market. By demonstrating the importance of foreign trade in Türkiye and in other CCs, we can observe its impact on the future integration process of these countries. The research results contribute to the theory and empirical study of European integration,

particularly regarding the Common Agricultural Policy (CAP). The study's comprehensive and multi-directional approach, along with its findings, provides valuable insights for both Turkish agricultural policy and the CAP.

The remainder of this article is organized as follows. Section 2 provides a literature review, while Section 3 details the methodology. Section 4 presents the results and discussion, while Section 5 concludes.

Literature Review

Agriculture is one of the most sensitive economic sectors worldwide. Nevertheless, agri-food exports have several economic benefits, stimulating a wide array of industries linked to the sector, including transportation, processing, and farm-input supply. Furthermore, most of the future growth in food demand is expected to occur in developing countries (McMinimy et al. 2017:2). Several factors, including increased trade liberalization, population growth, urbanization, and changing diets, have driven a significant increase in international trade in agri-food (Anderson 2010:3007). However, countries must also navigate several challenges, such as climate change, deteriorating soil conditions, and the loss of biological diversity (Shemshad 2025:279).

Although European countries currently have the largest share of world food exports, agri-food exports from developing nations are expanding rapidly, particularly from low- and middle-income countries in Africa, Asia, and South America. This strong expansion of agri-food trade coincides with important changes in the structure of trade (Aksoy and Ng 2010:2). While the importance of high-value food products – such as fruit, vegetables, and products of animal origin – is increasing in agri-food trade, the importance of staple food products, including cereals and traditional tropical commodities, has decreased. Such a changing structure of exports can be observed especially in developing countries (Diop and Jaffee 2005:237).

Globalization and participation in international trade have fostered economic growth in developing countries. Trade in high-value agri-food products has been argued to be particularly promising for fostering agricultural growth and rural development in low-income countries because of higher revenues (relative to lower-value staple food and raw commodity exports) and labor-intensive production systems. Due to the unique characteristics of the agricultural sector, countries often pursue similar objectives that contribute to higher levels of agricultural protectionism, especially in times of uncertainty. These objectives include ensuring food security for consumers, achieving self-sufficiency, maintaining a variety and quality range of products, stabilizing markets, mitigating the impact of global disturbances such as wars or natural disasters, protecting against uncontrolled imports of genetically modified (GM) foods, and preventing the spread of animal diseases (Gombkötő 2019:108).

In Türkiye and many other potential EU member countries, the agricultural sector plays a significant role. This importance is due to the sector's substantial contributions to GDP, employment, and trade. Additionally, trade liberalization at the regional level was enhanced through the establishment of the renewed Central European Free Trade Agreement (CEFTA) in 2006. Despite notable improvements, these countries still face challenges with export competitiveness. Over the long term, agricultural exports could enhance the export performance of EU CCs. However, exports

tend to decrease as the distance between trading partners increases, and this decline becomes more pronounced with greater distances. Consequently, the marginal decline in exports grows as the geographical distance expands. Overall, trade liberalization has positively impacted the export performance of EU CCs and provided them with the opportunity to become competitive on the EU market.

Considering the importance of the Turkish agricultural sector to both the national economy and the EU, several studies have analyzed the competitiveness of Turkish foreign trade in agri-food products, mainly analyzing the RCA, TBI, RSCA, and Grubel-Lloyd indices. These analyses demonstrated that Türkiye is mainly competitive in the fruit and vegetable market. For example, Sahinli (2014) examined Türkiye's international competitiveness between 2000 and 2011, Bashimov (2017) covered the period 2002–2015, and Bashimov, Çiçek, and Aydın (2017) examined the competitiveness of selected food products from 2001–2015. Similarly, Tatar (2020) examined Türkiye's competitiveness with that of neighboring countries, while Yılmaz and Genç (2021) focused on 2010–2019, and Yıldız (2022) analyzed its competitive position relative to selected global markets from 2002 to 2020.

Nevertheless, few studies compare the competitiveness of Turkish agri-food trade with that of other EU CCs. Thus, this paper addresses a gap in the literature by providing an international approach to agri-food competitiveness using a diverse set of indicators. In this respect, the approach proposed in this paper differs from the previously cited analyses.

Research Methodology

This study examines the competitiveness of Turkish agri-food foreign trade in comparison to that of other EU CCs (Albania, Bosnia and Herzegovina, Georgia, North Macedonia, Moldova, Montenegro, Serbia, and Ukraine). It analyzes the volume of agri-food exports and imports, providing an overview of Türkiye's current position within the EU agri-food market. The following products were selected for analysis: cereals, fruit, vegetables, beef and veal, sheep and goat meat, and milk and eggs, as these represent important components of agricultural production for most CCs. The study covers the period 2012–2022, as many of the analyzed countries attained CC status during this time. The choice of this timeframe effectively captures structural breaks, such as the COVID-19 pandemic, currency crises, the war in Ukraine, and the Black Sea Grain Corridor agreement. Relevant data on agri-food trade flows were primarily obtained from the Food and Agriculture Organization (FAO). The analysis employs basic descriptive statistics alongside the following competitiveness indicators based on the methodology proposed by Pawlak (2013).

The import penetration rate (*MP*) indicates the share of total domestic demand met by imports.

$$MP = \frac{M}{Q - X + M}, \tag{1}$$

where:
M – imports,
X – exports,
Q – production.

The export-import coverage ratio (*CR*) shows whether a country has a foreign trade deficit or surplus: a value below 100 indicates a deficit, whereas a value above 100 indicates a surplus.

$$CR = \frac{X}{M} \cdot 100\%, \tag{2}$$

where:
X – exports,
M – imports.

The export specialization index (*SI*) indicates a country's level of export competitiveness relative to the EU average. An *SI* value greater than 1 signifies that the country has above-average expertise and is competitive and specialized in exporting that product. An *SI* value of 1 indicates export performance similar to the EU average, while a value below 1 indicates that the country is not competitive or specialized in exporting that product.

$$SI = \frac{x_{ij}}{X_{it}} : \frac{m_{kj}}{M_{kt}}, \tag{3}$$

where:
x_{ij} – export value of product *j* for country *i*,
X_{it} – total exports of country *i*,
m_{kj} – import value of product *j* in market *k*,
M_{kt} – total imports in market *k*.

The relative comparative advantage in export (*XRCA*) reflects the degree of comparative advantage for a particular product. An *XRCA* greater than 1 indicates that a country exports the product more intensively than the EU average, demonstrating a comparative advantage and competitive strength in that product. An *XRCA* value equal to 1 signifies that the country's export share matches the EU average, while a value below 1 indicates the absence of a comparative advantage and low competitiveness.

$$XRCA_{ij=} = \frac{X_{ij}}{\sum_i X_{ij}} : \frac{\sum_j X_{ij}}{\sum_i \sum_j X_{ij}} \tag{4}$$

where:
X_{ij} – exports of product *i* by country *j*,
$\Sigma_i X_{ij}$ – total exports of all products by country *j*,
$\Sigma_j X_{ij}$ – total exports of product *i* by all countries in the reference group,
$\Sigma_i \Sigma_j X_{ij}$ – total exports of all products by all countries in the reference group.

The index of relative import absorption (MRCA) measures a country's import intensity of a particular product relative to the EU average. An MRCA value greater than 1 indicates that the country imports a larger share of the product than the EU average, reflecting higher demand or greater dependence on it. A value of 1 signifies a share matching the EU average, while a value below 1 reflects lower demand or reduced dependence on the product.

$$MRCA_{ij=} = \frac{M_{ij}}{\sum_i M_{ij}} : \frac{\sum_j M_{ij}}{\sum_i \sum_j M_{ij}} \tag{5}$$

where:
M_{ij} – imports of product *i* by country *j*,

$\Sigma_i M_{ij}$ – total imports of all products by country *j*,
$\Sigma_j M_{ij}$ – total imports of product *i* by all countries in the reference group,
$\Sigma_i \Sigma_j M_{ij}$ – total imports of all products by all countries in the reference group.

The relative trade advantage index (*RTA*) indicates whether a country is a net exporter or importer of a particular product. An *RTA* greater than 0 signifies that the country exports more than it imports, demonstrating a comparative advantage, whereas a value less than 0 reflects a comparative disadvantage. An RTA of 0 indicates that exports and imports are balanced.

$$RTA = XRCA - MRCA. \tag{6}$$

The self-sufficiency indicators were calculated using the following formula recommended and used by the FAO:

$$\text{Self-sufficiency level} = \frac{\text{Production}}{\text{Production} + \text{import} - \text{export}} \cdot 100\%. \tag{7}$$

Based on this calculation, the CCs are listed by their average self-sufficiency rate between 2012 and 2022.

Results and Discussion

Türkiye is self-sufficient in most agri-food products (Table 1). An analysis of the overall self-sufficiency indicators demonstrates that the country maintains high levels for all products; the lowest are for cereals and sheep and goat meat (around 80%), while for the remaining products, indicators remain around or above 100%. Türkiye achieved its highest indicator for eggs (131%), which is the highest among the analyzed countries, followed by fruit (112%) and vegetables (106%). Self-sufficiency for milk and beef is approximately 100%.

Table 1. Average food self-sufficiency of candidate countries, 2012–2022 (%)

	Cereals	Fruit	Vegetables	Milk	Eggs	Beef and Buffalo Meat	Sheep and Goat Meat
Albania	72	96	106	99	101	95	45
Bosnia and Herzegovina	72	72	95	100	107	37	93
Georgia	42	100	83	87	98	89	155
Moldova	167	129	96	90	99	121	468
Montenegro	13	63	59	85	72	50	92
North Macedonia	82	117	118	90	89	29	331
Serbia	143	113	104	98	100	103	73
Türkiye	80	112	106	101	131	99	82
Ukraine	293	83	100	103	104	109	73

Source: own calculations based on FAOSTAT n.d.

The share of imports of most agricultural products decreased in most of the analyzed countries during the years under review. In Serbia, this share remained stable, while in Türkiye and Ukraine, it increased, averaging around 6%. Despite this increase, Türkiye has the lowest share among the countries considered, reflecting its favorable climatic conditions and low dependence on agri-food imports (Table 2).

Regarding the share of agricultural product exports in total exports, as total exports increased, the agricultural export rate also increased in Türkiye, Albania, Georgia, Moldova, and Ukraine, although in Türkiye it increased only slightly (Table 3).

Table 2. Agricultural imports among total imports in candidate countries, 2012–2022 (%)

Agricultural Import (%)	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Albania	17	18	17	16	16	17	16	17	17	21	18
Bosnia and Herzegovina	18	18	17	18	18	16	16	16	17	15	14
Georgia	17	19	18	18	17	16	16	15	17	15	16
Moldova	17	17	15	16	15	14	14	14	16	14	14
Montenegro	24	23	24	24	21	21	20	21	20	21	18
North Macedonia	13	13	11	11	11	10	9	9	10	9	9
Serbia	9	9	10	10	10	10	9	9	10	9	9
Türkiye	5	5	6	6	6	6	6	8	8	7	7
Ukraine	8	9	9	9	10	9	9	10	12	11	10

Source: The Observatory of Economic Complexity n.d.

Table 3. Agricultural exports among total exports in candidate countries, 2012–2022 (%)

Agricultural Export (%)	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Albania	6	6	7	8	9	9	10	11	13	11	10
Bosnia and Herzegovina	7	7	7	9	9	9	7	7	8	6	6
Georgia	18	22	25	23	28	24	25	21	24	23	19
Moldova	33	37	39	41	42	42	37	38	38	39	40
Montenegro	10	16	22	20	21	7	11	11	18	18	5
North Macedonia	14	15	12	12	12	12	9	9	11	9	8
Serbia	24	19	21	23	23	20	18	19	22	20	17
Türkiye	10	11	12	12	12	11	11	11	12	11	12
Ukraine	25	27	30	37	41	39	37	43	45	41	52

Source: The Observatory of Economic Complexity n.d.

Looking at trading partners, all CCs except Türkiye mainly import agricultural goods from neighbors or maritime neighbors. Partner countries remained largely the same between 2012 and 2021 (Table 4). Due to historical ties, Russia, the United States and Germany were among Türkiye's main import partners.

The main export partners closely mirror the import partners (Table 5). These partnerships are mostly established with land-border neighbors. However, in a departure from import patterns, Iraq was the main agricultural export partner for Türkiye for all the years analyzed; in 2021, the United States became the second largest export destination for Türkiye.

Table 4. Main agricultural import partners of EU candidate countries, 2012–2021

	2012	2013	2015	2016	2019	2021
Albania	Italy	Greece	Italy	Italy	Italy	Italy
Bosnia and Herzegovina	Croatia	Serbia	Serbia	Serbia	Serbia	Serbia
Georgia	Ukraine	Ukraine	Ukraine	Ukraine	Ukraine	Ukraine
Moldova	Ukraine	Ukraine	Ukraine	Ukraine	Ukraine	Ukraine
Montenegro	Serbia	Serbia	Serbia	Serbia	Serbia	Serbia
North Macedonia	Serbia	Serbia	Serbia	Serbia	Serbia	Serbia
Serbia	Croatia	Germany	Croatia	Belgium	Germany	Germany
Türkiye	Germany	U.S.A.	Russia	U.S.A.	Russia	Russia
Ukraine	Russia	Russia	Russia	Germany	Poland	Poland

Source: WITS (World Integrated Trade Solution) n.d.

Table 5. Main agricultural export partners of EU candidate countries, 2012–2021

	2012	2013	2015	2016	2019	2021
Albania	Italy	Italy	Italy	Italy	Italy	Italy
Bosnia and Herzegovina	Croatia	Croatia	Croatia	Croatia	Croatia	Serbia
Georgia	Ukraine	Russia	Russia	Russia	Russia	Russia
Moldova	Russia	Russia	Belarus	Romania	Romania	Romania
Montenegro	Serbia	Serbia	Serbia	Serbia	Serbia	Serbia
North Macedonia	Serbia	Serbia	Serbia	Serbia	Serbia	Serbia
Serbia	Bosnia	Bosnia	Bosnia	Bosnia	Bosnia	Bosnia
Türkiye	Iraq	Iraq	Iraq	Iraq	Iraq	Iraq
Ukraine	Russia	Russia	Belarus	Belarus	Belarus	China

Source: WITS (World Integrated Trade Solution) n.d.

Table 6 shows the share of primary products within Türkiye's total agricultural exports. Türkiye is recognized as one of the EU's biggest partners for fruit and vegetable imports. After 2018, the depreciation of the Turkish lira made Turkish products more competitive abroad, leading to increased exports. This situation also had a positive impact on grain exports. In 2022, Türkiye, Ukraine, Russia, and the United Nations established the Black Sea Grain Corridor Agreement, which ensures the safe transport of grain and food products through the Black Sea. This agreement helped stabilize global food prices while also enhancing the presence of Turkish flour in export markets. The increase in the share of cereal exports consequently affects the shares of other agricultural goods, among which, fruit accounts for the highest share (approximately 50%), while vegetables represent a much lower share (around 30%).

Table 6. Share of exports of main products among total agricultural exports of Türkiye, 2012–2022 (%)

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Cereals	7	9	3	4	2	4	3	15	11	11	17
Fruit	55	55	56	60	58	58	62	52	57	53	50
Vegetables	31	29	32	30	26	27	25	24	26	27	25
Milk	1	2	3	2	8	5	4	6	3	6	5
Eggs	5	6	6	4	5	6	6	4	3	3	3

Source: FAOSTAT n.d.

Table 7 shows the share of the most significant products in Türkiye's agricultural imports. Türkiye imports almost 95% of its cereals, and the share of imports in cereals increased by almost 6%. However, the share of imports for other goods decreased. Cereal production is not sufficient for the large population, and there is a huge demand for cereal-based foods due to dietary habits. Furthermore, climatic conditions have been unfavorable for cereal production in recent years. In contrast, goods such as fruit and vegetables are produced in sufficient amounts due to the suitable climate. According to FAOSTAT reports, Türkiye ranks third globally for cereal imports.

Table 7. Share of imports of main products among total agricultural imports of Türkiye, 2012–2022 (%)

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Cereals	90.0	91.3	92.9	90.6	90.3	93.1	93.8	93.2	93.4	94.4	95.5
Fruit	6.8	5.9	4.7	6.3	7.1	5.3	4.3	4.6	5.2	5.0	3.4
Vegetables	0.8	0.7	0.6	0.8	0.8	0.5	0.4	1.3	0.6	0.4	0.8
Milk	1.9	2.0	1.8	2.0	1.7	0.8	0.8	0.7	0.8	0.2	0.3
Beef and Buffalo Meat	0.5	0.1	0.0	0.3	0.1	0.2	0.6	0.1	0.0	0.0	0.0

Source: FAOSTAT n.d.

The per capita import of the primary agri-food products was also analyzed (Table 8). Cereals stand out, with imports increasing over the study period to 144 kg per person the second highest among the analyzed countries after Bosnia and Herzegovina. This increase resulted from rising production

costs, economic and currency instability, and drought risks in the Anatolia region, the center of Turkish grain production.

Table 8. Import of selected agri-food products in Türkiye, 2012–2022 (kg per capita)

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Cereals	64	77	98	63	50	77	88	154	134	139	144
Fruit	5	5	5	6	5	5	5	9	9	9	5
Vegetables	0.6	0.6	0.7	0.8	0.6	0.6	0.5	3	1	0.9	2
Milk	1	2	2	2	1	0.8	0.9	1	1	0.3	0.5
Eggs	0,01	0,02	0,03	0,03	0,03	0,03	0,04	0,06	0,03	0,03	0,03
Beef and buffalo meat	0.34	0.08	0.01	0.25	0.09	0.23	0.73	0.10	0.08	0.03	0.03
Sheep and goat meat	x	x	x	x	x	x	0.002	0.001	0.002	0.005	x

Source: FAOSTAT n.d.

Fruit also deserves attention, although its per capita import is much smaller averaging only 6 kg per person the lowest among the CCs. Favorable climatic conditions, diverse production, and improving production techniques result in lower import levels. The other CCs and Türkiye maintained relatively stable production between 2012 and 2022.

A different situation is observed in egg imports. The import was about 30 g per person, becoming one of the lowest among the analyzed CCs, similar to Ukraine. The decline stemmed from the expansion of domestic poultry production and the impact of avian flu on the European egg market.

Beef and buffalo meat production was insufficient in CCs, rendering these countries net importers. In Türkiye, imports of beef and buffalo meat decreased in the years under review due to the 2018 currency crisis, which affected the Turkish economy; government attempts to stabilize prices did not prove effective. Per capita imports of beef and buffalo meat were calculated at 730 g per person, but in subsequent years, they declined to lower levels similar to those in earlier years. Throughout the study period, it remained one of the lowest among the analyzed countries, comparable to the indicator for Ukraine. Similarly, sheep and goat meat are not prominent import commodities because breeding sheep and goats is easier than raising cattle. All analyzed countries maintained imports of less than 100 g of sheep and goat meat per person, which is consistent with local dietary habits.

Türkiye and Ukraine also have lower levels per capita of milk imports (below 1 kg per person) in most years, which decreased in the years studied. Furthermore, Turkish vegetable imports per person are the lowest among the analyzed CCs. In most of the years analyzed, it remained below 1 kg, despite an increase every year.

Competitiveness has been defined in various ways, reflecting its multiple dimensions. Originally, in the context of international trade, competitiveness was understood as price or cost competitiveness, which refers to relative export prices or terms of trade, whereby a country's domestic prices or costs are compared with respective international prices or costs. In contrast, non-price competitiveness

is not directly related to prices or costs. Instead, it encompasses a broader range of factors and captures a multitude of dimensions both quantitative and qualitative that influence a country's trade performance and openness. The World Economic Forum defines competitiveness as "the set of institutions, policies, and factors that determine the level of productivity of a country" (Bardaka and Rentifi 2021:61).

Selected competitiveness indicators were calculated for the 2012–2022 period (Table 9). The MP in Türkiye increased only for cereals, averaging 21% a level similar to that of North Macedonia. The CR shows that Türkiye like Albania, Bosnia and Herzegovina, Georgia, and Montenegro maintained a trade deficit in cereals. Results for the SI and XRCA show that Türkiye lacked greater cereal export experience than the EU average. According to the MRCA, Türkiye had a higher import share of cereals than the EU average as rising energy costs drove import levels to meet demand. The RTA confirms that Türkiye is a net cereal importer, while only Moldova, Serbia, and Ukraine are net exporters.

Table 9. Competitiveness indicators for selected Turkish agri-food products, 2012–2022

	MP		CR		SI		XRCA		MRCA		RTA	
	2012	2022	2012	2022	2012	2022	2012	2022	2012	2022	2012	2022
Cereals	13	28	14.5	24.2	0.2	0.3	0.08	0.1	5.72	8.87	−5.64	−8.74
Fruit	2	2	2740.9	5895.5	4.5	3.6	11.40	6.3	0.19	0.08	11.21	6.21
Vegetables	0	0	766.6	809.8	1.4	1.8	1.48	2.2	0.18	0.29	1.30	1.88
Milk	1	0	0.0	5.9	0.0	0.0	0.0	0.0	0.01	0.01	−0.01	−0.01

Source: own calculations based on Eurostat n.d.

Türkiye's climate is conducive to the production of different types of fruit such as citrus, bananas, and melons. The adoption of new technologies and agricultural policies further increased production and export volumes. The MP indicates that Türkiye imports less fruit than cereals; the share of domestic fruit demand met by imports averages around 2%, a level similar to that of Moldova. The CR indicates that Türkiye maintains the highest surplus for fruit trade among the analyzed CCs, and this indicator more than doubled in the analyzed years. The SI shows that Turkish fruit exports, along with those of Albania, Georgia, and Montenegro, are higher than the EU average. The XRCA indicates that CCs excluding Moldova, Serbia, and Ukraine export more fruit than the EU average, with Türkiye attaining the second-highest value behind Georgia. Only in Türkiye is the MRCA of fruit lower than the EU average across all analyzed years. Consequently, the RTA indicates that Türkiye, alongside Georgia, is a net exporter of fruits.

It is clear that the countries with a Mediterranean climate such as Türkiye, Albania, North Macedonia, and Serbia have strong vegetable exports. In particular, Türkiye and Serbia, which pursue more aggressive trade strategies in agricultural products, have reduced North Macedonia's market share. The MP demonstrates that Türkiye, alongside Albania, Bosnia and Herzegovina, North Macedonia, and Ukraine, had the lowest import rates for vegetables. The increasing dependence on imports is mainly due to the lack of local supplies during the off-season. The CR shows that Türkiye and North Macedonia both maintained a surplus in all years, with the Turkish surplus being the largest. Although fluctuations were recorded, the surplus persisted. The SI shows that Türkiye,

along with Albania, Bosnia and Herzegovina, Montenegro, and North Macedonia, had higher export levels than the EU average. Similarly, the XRCA shows that Türkiye along with Albania, Montenegro, and North Macedonia exported more vegetables than the EU export average, confirming its standing in vegetable production and trade. Finally, the MRCA shows that Türkiye's average vegetable imports were lower than the EU average. Consequently, the RTA indicates that Türkiye, along with Albania, Bosnia and Herzegovina, and North Macedonia, is a net exporter of vegetables, and the value of this indicator has increased over the analyzed years.

Milk exports in Türkiye were among the highest of the CCs comparable to those of Ukraine because Türkiye increased its export rate more than ninefold from 2012 to 2022. This increase was mainly due to increased production capacity, the modernization of quality standards, and the depreciation of the Turkish lira, allowing Turkish dairy products to be sold at more competitive prices in international markets. Consequently, the MP results confirm that Türkiye, along with Albania and Ukraine, had the lowest milk import levels among the CCs. The CR indicates that all CCs had a foreign trade deficit. The SI shows that all the CCs had a much lower level of export specialization than the EU average. The XRCA shows that none of the CCs have a comparative advantage in milk exports. Potential reasons include a lack of alignment with EU quality standards and insufficient control mechanisms on livestock farms. The MRCA indicates that all analyzed countries have lower average milk imports than the EU. Thus, the RTA shows that most of the CCs are net importers of milk except Bosnia and Herzegovina; however, Türkiye, North Macedonia, and Ukraine have the chance to transition from net importer to net exporter, as the value is very close to 0.

Conclusions

This study examined the competitiveness of Turkish agri-food foreign trade relative to other CCs. Through a detailed analysis of trade flows and the factors influencing competitiveness, the research offers critical insights into Türkiye's standing in the agri-food sector. Due to the size of the country and the importance of the agricultural sector and agri-food trade with the EU, the findings are significant for understanding both foreign trade competitiveness and the potential implications for the CAP.

1. Türkiye is self-sufficient in almost all analyzed agri-food products, with indicators at approximately 100%, except for cereals and sheep and goat meat, which averaged 80%.
2. The analysis shows that while both the share of exports and imports of agri-food products in Türkiye's total trade has gradually increased over the years under study, the import share remains among the lowest compared to the other analyzed countries.
3. Throughout the period, Türkiye's agri-food exports were dominated by fruit, at approximately 50%, followed by vegetables at 30%; in terms of imports, cereals dominate with a share of approximately 90%.
4. The analysis of competitiveness indicators revealed that Türkiye stands out from the other CCs with particularly high competitiveness in the fruit and vegetable markets.

5. Türkiye has emerged as a dominant player among the CCs due to its extensive agricultural land and diverse climatic conditions, which enable a varied agricultural output. However, significant challenges hinder Türkiye's full potential in the global agri-food market, including infrastructural gaps, economic fluctuations, inconsistent trade policies, and variable quality standards.

6. Macro-economic factors, including GDP growth, population trends, and economic stability, play a crucial role in determining competitiveness. Türkiye's relatively robust economic growth and increasing population provide a solid foundation for its agri-food sector, contrasting with the declining populations and economic challenges faced by some other CCs.

7. The policy environment is also critical to enhancing competitiveness. Türkiye's current policies need significant reforms to improve infrastructure, streamline regulations, and foster innovation. Enhanced institutional support, particularly in research and development, and capacity-building initiatives for farmers, is essential to address existing weaknesses and leverage Türkiye's agricultural potential.

While Türkiye demonstrates strong foundational attributes for competitive agri-food trade, strategic policy interventions are crucial to overcome current challenges and achieve competitiveness on the EU market.

To sum up, in Türkiye and in most CCs, the level of agricultural development and productivity is much lower compared to the EU average and is quite diversified. This is due to the low level of development of these countries, a lack of investment in the agricultural sector, limited access to foreign markets, and low productivity, which also results from their historical development. The situation of the agricultural sector and agricultural production was also significantly influenced by numerous changes, including the collapse of the USSR and the war in the former Yugoslavia, as well as the agricultural reforms carried out. Therefore, the chances of Türkiye and other CCs achieving future competitiveness on the EU market are often limited.

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Comparative Economic Research. Central and Eastern Europe
Volume 29 Number 3, 2026
https://doi.org/10.18778/1508-2008.29.21

From Behind the Great Wall with (No) Strings Attached? Visegrád Group Vulnerabilities and Dependencies on Chinese Dual-Use Imports

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Abstract

This paper examines the dependence of the Visegrád Group (V4) economies on imports of advanced dual-use goods from China. Using frameworks of international political economy, economic security, and weaponised interdependence, dual-use items are treated as potential geoeconomic leverage. Vulnerability areas are identified through the analysis of trade in value added, intra-industry trade, and strategic import dependencies. The findings show a growing share of Chinese value added in V4 final demand and exports, reinforcing structural dependence in machinery, automotive, electronics, optics, and chemicals. On the one hand, weak comparative advantages and external vulnerabilities limit the V4's resilience and position in global value chains. On the other hand, however, the intensity of the intra-industry trade suggests untapped potential for upgrading domestic production of dual-use goods. Recommendations include strengthening national and EU capabilities in dual-use clusters, regionally coordinated development of R&D ecosystems, leveraging knowledge-intensive services, prioritising European content, and improving analytics to map critical nodes, as well as direct and indirect dependencies.

Keywords: dual-use, V4 economies, China, economic security, resilience
JEL: F14, F15, F52

Funding information: University of Wrocław, Wrocław, Poland.
Conflicts of interests: None.
Ethical considerations: The Author assures of no violations of publication ethics and takes full responsibility for the content of the publication.
Received: 9.02.2026. Verified: 17.03.2026. Accepted: 24.06.2026

Introduction

For many years, China's economic and technological power evolved under a low-profile approach, while the neoliberal globalisation paradigm simultaneously privileged low production costs within global value chains (GVCs). Together, these dynamics facilitated China's emergence as the "Factory of the World". This transformation was reinforced by its innovation-driven development strategy and industrial policy, which were based on the idea that China had a once-in-a-lifetime opportunity to get in on the ground floor of a technological revolution and vault into the leading ranks of economic and technological powers (Naughton 2021). During the same period, the European Union (EU) adhered to a stance of liberal pragmatism, prioritising economic benefits on the one hand, while expressing inconsistent reservations regarding human rights protection on the other (see Brown 2018; Fulda 2024). Under these conditions, a critical inflexion point went largely unnoticed: the relocation of environmentally and socially "dirty processes" translated into overdependence on Chinese inputs. As a consequence, this dependence has enabled China to leverage economic relations and its geostrategic priorities, including efforts to reconfigure the international order (see Blackwill and Harris 2016; Spalding 2022; Zenglein 2024; Sinkkonen 2025).

A clear manifestation of this asymmetry is the weaponisation of interdependencies through mechanisms such as the panopticon and chokepoint effect (Fjäder 2018; Farrell and Newman 2019). These dynamics of new threats intensify the quest for technological leadership, which in turn amplifies the geopolitical motivations to control critical elements of production networks. Escalations in trade tensions and the calibration of economic pressure also extend to dual-use goods. Against this background, efforts to restore the EU's innovation capacity and competitiveness (see Draghi 2024) encounter mounting obstacles, particularly in industries combining highly advanced, energy-efficient production with knowledge-intensive services.

In response to these challenges, the EU has begun to broaden its toolkit beyond mere export controls. The new mix aims at the adoption of an economic security strategy (European Commission 2023; see Rosén and Meunier 2023), safeguarding against economic coercion (ACI; see Szép 2024), the introduction of new tariffs, enhanced FDI screening, security of research and technology transfer, as well as provisions on critical raw materials (CRM). Importantly, growing awareness of vulnerabilities is accompanied by a more systemic diagnosis of bottlenecks and the identification of necessary countermeasures. Nevertheless, the formulation of comprehensive responses remains a significant challenge. Critics argue that this pattern reflects deeper problems, including power understood as a destructive ability not to learn, collective complacency, self-imposed circumvention of constraints, and a form of triadic thinking, wherein China is framed as a partner, competitor, and geopolitical rival (see Fulda 2024; Stec 2025).

Against this background of growing volatility and uncertainty, the international environment is undergoing a gradual shift towards sceptical liberalism (see Nissen and Dreyer 2024). This change may prove decisive for reshaping the practice of European strategic autonomy (see Helwig and Sikkonnen 2022), as its primary attention turns towards eroding interdependencies (see Roberts, Choer Morales, and Ferguson 2019). Within this context, the perception of both traditional and emerging threats reinforces

the return of industrial policy (see Evenett et al. 2024) as well as initiatives aimed at strengthening economic security and resilience.

These dynamics constitute a key dimension of the international economic policies of the Visegrád Group (V4) countries. Operating within their current development model, they seek to avoid being trapped in a (semi-)peripheral status and instead strive to strengthen their position within the EU and the global economy. Given the integration of V4 economies into European production networks (Vlčková 2018; Cieślik 2019), supply chain resilience is of critical importance to their long-term prospects. At the same time, however, new challenges and potential tensions are emerging. From a structural perspective, one such challenge stems from the growing similarity of Chinese exports and those originating from the V4 (Javorčik 2025; WTO 2025), which may intensify competitive pressures in key sectors.

The structure of the paper is as follows. Section 2 outlines the research objectives and methodological approach. Drawing upon a comprehensive literature review in Section 3, I situate the research question within the academic discourse, thereby providing a framework for contextualising novel findings in Section 4. These findings serve then as the basis for discussion and the formulation of policy recommendations in Section 5. The last section concludes.

Research Objectives and Methods

The research inquiry zeroes in on the V4's import dependencies on technologically advanced dual-use goods originating from China. The primary objective is to evaluate the potential ramifications of vulnerability. I argue that excessive exposure to uncertain supplies and disruptions may undermine the strategic autonomy of the EU while adversely affecting the structural competitiveness of the V4 economies. This vulnerability is also linked to their development pattern, which relies on trade openness and the inflow of foreign direct investment (see Nölke and Vliegenthart 2009; Bohle and Greskovits 2012). These are pivotal factors determining regional and global value chains as well as the position of the V4 economies.

Against this backdrop, this research is positioned at the intersection of international political economy, international economics, and economic security. It also aligns with the growing body of scholarship arguing that the boundaries between the traditional security agenda and economic matters have become increasingly blurred (see Drezner 2024). In this context, drawing on the theory of trade expectations (Copeland 2014), increased instability in strategic trade flows combined with asymmetries may elevate the likelihood of weaponised interdependence (Farrell and Newman 2019). Such conditions provide a rationale for both offensive measures, such as the diversification of supply sources, and defensive ones, including the regulation of access to domestic markets. Nevertheless, their implementation tends to give rise to a sequence of tensions typical of the security dilemma, as actions launched to enhance resilience may be interpreted as threats by other parties.

It is precisely within the nexus of trade and security competition that dual-use goods acquire particular relevance. Due to their military and civilian applications, they constitute an efficient tool to influence the developmental trajectories of existing partners/rivals. Disruptions and modified dynamics of so-called coopetition may directly affect national security outcomes (see Pandiyan and Schild 2025;

Svetlicinii and Su 2025). Moreover, the classification of dual-use goods overlaps with sectors of strategic importance for the EU's competitiveness, including defence, space, clean-tech, bio-tech, and med-tech, which may amplify systemic risks.

At the empirical level, the research draws on trade statistics sourced from the OECD (2025c), Eurostat (2025), and the International Trade Centre (ITC 2025). The analysis is conducted at the 6-digit level of data disaggregation (HS6). In order to identify areas of dependency and vulnerability related to dual-use goods, I triangulate complementary measures: the symmetrical revealed comparative advantage (SRCA); the Grubel-Lloyd Index (GLI), which captures the intensity of intra-industry trade and distinguishes between its horizontal and vertical components; the Herfindahl-Hirschman concentration index (HHI); diagnostics of strategic dependencies by the European Commission (2021); and the external vulnerability index (Garcia and Ho 2025).

By combining these methods, the analysis provides a comprehensive identification of dual-use product clusters wherein dependencies on China are most pronounced. According to the classification of the European Commission (2024), the list of dual-use goods comprises 1,251 HS8 items, which, upon aggregation to the HS6 level, results in 851 product categories. This classification is key to national security as it translates into the scope of export controls, considering the context of technological sovereignty, trade sanctions, the risk of their circumvention, and long-term implications for international peace. Within this set, a total of 140 HS6 clusters fall within strategic industries, while 603 clusters are classified as mid-tech (MT), mid-high-tech (MHT), and high-tech (HT) categories. This distribution underscores the technological intensity of the dependencies examined here.

However, the study is subject to certain methodological limitations. The emphasis placed on direct bilateral trade relations does not fully capture the complexity of production networks or the pressures which may be transmitted through multi-tiered supply chains. As noted by Šebeňa, Chan, and Šimalčík (2023), traditional bilateral trade statistics provide only an approximation of actual exposures; therefore, they tend not to reflect the true extent of exposure to China. In practice, the real level may be up to twice as high as that in officially reported figures. To address this, insights from Trade in Value Added (TiVA) covering direct and indirect links provide a more comprehensive picture.

Literature Review

Dual-use goods as a likely mechanism of pressure exerted by China towards the V4, viewed through the lens of the EU's strategic autonomy, remains insufficiently addressed within contemporary scholarship. The following literature review, therefore, seeks to map an interdisciplinary field that sits at the intersection of international political economy, security studies, and EU external economic governance. By reflecting on and synthesising related findings, I outline recent research paths, identify the gap motivating this inquiry, and highlight implications that are relevant to evidence-based public policy.

Against this background, the foundational premise of this investigation is articulated by Brown (2018), who argues that the EU did not adequately anticipate the implications of China's rise, which in turn contributed to the absence of a coherent policy for building substitution capacity and the pursuit of strategic

autonomy. As a result, contemporary policy responses often appear improvised and delayed rather than logically sequenced. This matters particularly for the V4 economies. Their weaker competitiveness, less advantageous position within GVCs, and fragile linkages between international companies and domestic suppliers and the R&D sector (see Vlčková 2018) increase their exposure to external shocks and supply-side disruptions. In other words, these structural features of the development model translate into specific vulnerabilities amidst increasingly contested external circumstances.

These vulnerabilities also become more salient as Chinese corporate presence and the share of Chinese value added expand (see Cieślik 2019). In line with the logic of weaponised interdependence (Farrell and Newman 2018), a deeper integration into China-centred production and technology networks may narrow the room and scope for potential countermeasures, especially when critical hubs and chokepoints lie beyond the EU's direct influence. This observation motivates, in turn, a more explicit geoeconomic examination of uncertainties, vulnerabilities, and the potential ramifications of external coercion. Put differently, it points to the securitisation of economic policy (see Roberts, Choer Moraes, and Ferguson 2019) and the associated conceptual challenges posed to policy-making. The EU's integration historically rooted in openness to trade and cooperation has also fostered a political mindset in which deep interdependencies are treated as a default good. Consequently, even when tensions and negative spillovers become obvious, it appears to be exceedingly difficult to challenge established assumptions and dominant thought patterns for policy scripts. The debates thus continue to be framed, to a large extent, by the paradigm of post-liberal management of complex interdependencies (see Nissen and Dreyer 2024), rather than by a decisive turn towards more robust economic security toolkits and actions.

For this reason, this orientation translates into a two-pronged policy. On the one hand, it prioritises maintaining dialogue, strengthening diversification, and adopting strategies such as de-risking or friend-shoring. On the other hand, it can imply a degree of hesitancy: an intellectual and institutional inability to pursue more definitive remedies and responses when interdependencies become channels of coercion. As Poutala, Sinkkonen, and Mattlin (2022) noted, divergent member-state interests and the constraints on the European Commission's competences can undermine the capacity to mitigate and de-weaponise external pressures. At the same time, the EU often operates in its institutional "comfort zone", which entails a proficient institutionalisation of response mechanisms, e.g., through ACI regulations, thereby activating its own bureaucratic apparatus (see Freudlsperger and Meunier 2024; Szép 2024).

Nevertheless, a key uncertainty remains as to whether such signalling and the communication of deterrence will translate into consistent actions. As Hrynkiv and Lavrijssen (2024) argue, WTO security exceptions appear poorly suited to the nature of contemporary geopolitical tensions. It is, therefore, unsurprising that scholarly and policy attention is gradually shifting towards the identification of critical dependencies and the specification of coercive scenarios, as the escalation of disputes amplifies the risk of new retaliatory measures and erosion of the liberal international order.

Within this evolving landscape, the position of the V4 economies is unique. Their attractiveness for foreign investment inflows remains robust and could facilitate near-shoring strategies (see Guerrieri and Padoan 2024), which suggests an opportunity to relocate selected stages of production closer to the EU core. Nonetheless, the same pattern may also reinforce a dependent development based

on FDI-led industrial transformation. As Éltető, Sass, and Götz (2022) posit, such a model would deepen the dualism between foreign-owned subsidiaries and the domestic SME sector. Moreover, the emergence of technologically advanced industrial production, driven by robotisation and the AI revolution, alongside the weak local linkages with the R&D sector, may entrench import dependence on China for key inputs. Consequently, what appears as industrial upgrading may reproduce external reliance, thereby complicating the implementation of the EU's strategic autonomy.

This concern is reinforced by more granular evidence on specific supply relations. According to the ETNC/Merics report (Andersson and Lindberg 2024), Europe is significantly dependent on Chinese sources for a range of components and materials, including but not limited to magnets, lithium, and photovoltaic parts and accessories. In this context, the V4 economies can function as a bridge to the EU market for China (see Pavlínek 2025) and compete among themselves. They also identify and respond differently to Chinese engagement in the region (see Melnychuk and Pavliuk 2025). Importantly, emerging tensions should not be interpreted solely as a bilateral EU-China dynamic. They may also reflect US diplomatic pressure and the extraterritorial application of US legal frameworks designed to curb China's and Europe's growth in areas of perceived vulnerability, including dual-use domains (see NSS 2025; Pandiyan and Schild 2025). This geopolitical setting matters because it shapes the range of incentives, limitations, and risk perceptions that must be taken into account in decision-making.

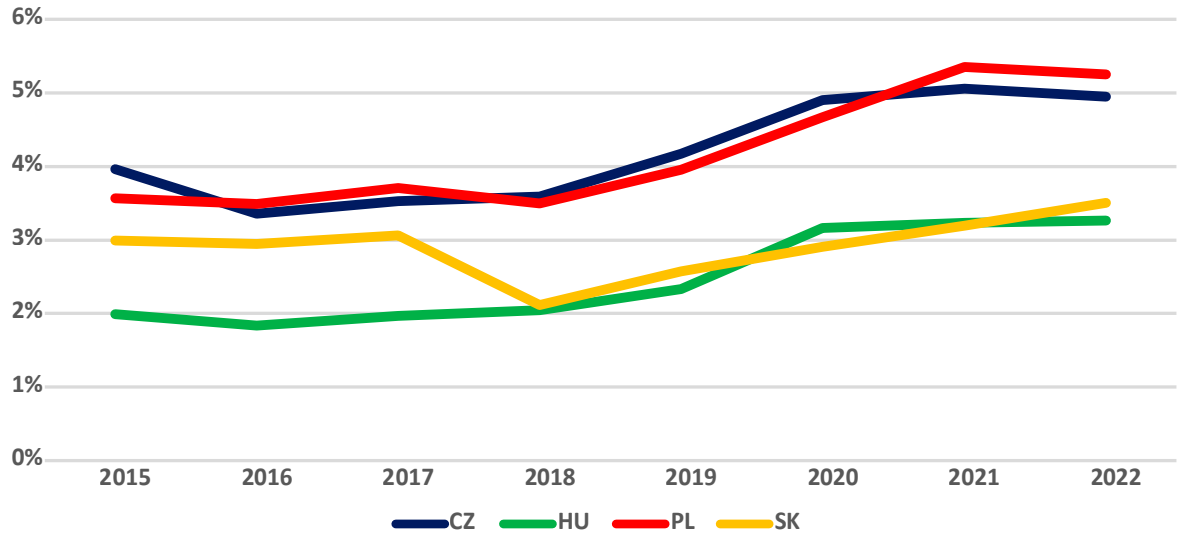
From this perspective, the stick-and-carrot approach suggests that green technologies may emerge as a salient area of both political pressure and technological inducements offered by China to the V4 countries. China's central position within these value chains amplifies the likelihood of creating bottlenecks, especially if V4 strategies aim to advance into segments of higher technological sophistication and complexity, which may also foster more intense intra-V4 rivalry. Higher exposure to import disruptions can thus be linked to limited substitution opportunities for components, stemming in part from the insufficient presence of local suppliers (see Qiu et al. 2025).

Furthermore, it is essential to recognise that the coercive throttling potential is gravitating towards deep tech domains such as AI, digital infrastructure, advanced materials, energy and chemical technologies. This shift broadens the discussion from narrow trade dependencies to questions about the degree and scope of supply diversification, as well as the capacity to promote frontier innovation and technological sovereignty, the latter being widely understood as a cornerstone of the EU's strategic autonomy (see Infuture Institute 2025).

Results

The dependence of the V4 economies on value added (VA) generated in China increased steadily between 2015 and 2022. To capture this tendency, I measure the share of Chinese VA in the total final demand for foreign VA in the V4 countries, with an adjustment that narrows the scope to industrial codes in which goods classified as dual-use are present (Chart 1). This refined approach covers categories B06, B07, and C19–C30 (see OECD 2025a; 2025b), thereby aligning the measurement more closely with the security-relevant dimension of trade dependencies. Both perspectives reveal that Chinese VA has become an important component of the V4's final consumption. Import dependence in terms of final demand is not evenly distributed across sectors; rather, it is

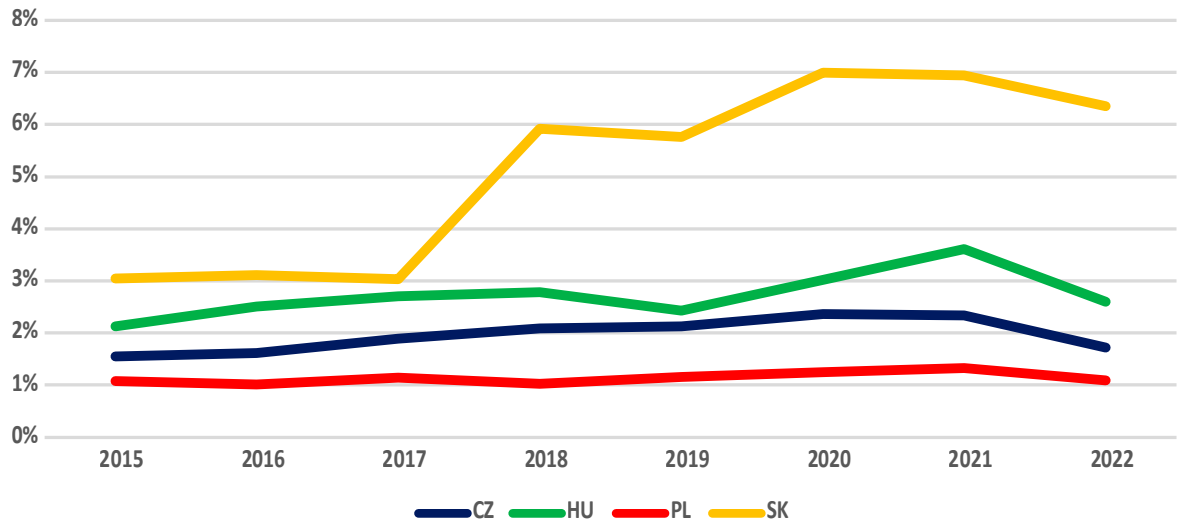
concentrated in particular categories that constitute the core areas of vulnerability: the manufacture of computer, electronic, and optical products (C26), the manufacture of electrical equipment (C27), the manufacture of machinery and equipment (C28), and the manufacture of chemicals and chemical products (C20).



* Codes B06, B07 and C19–C30.

Chart 1. Share of Chinese value added from selected sectors* in the final demand for foreign value added in the V4 economies, 2015–2022
Source: own study based on OECD 2025a; 2025c.

Given that the development model of the V4 economies is largely driven by export performance and participation within GVCs, it is also necessary to move from sectoral identification to a trade-embedded perspective. Accordingly, I examine the share of Chinese VA from the above-mentioned categories in the value of gross exports (Chart 2), as this captures how upstream dependencies may determine the competitive potential of each economy. The results suggest that the structure of Chinese VA differs across the V4, which reflects their distinct specialisations. In Czech exports, Chinese VA originates from the manufacture of motor vehicles, trailers, and semi-trailers (C29), the manufacture of computer, electronic, and optical products (C26), and the manufacture of electrical equipment (C27). In Hungary, it is derived from C29 and C26 (as above). In Poland, the largest contributions come from the mining of metal ores (B07) and C27. In Slovak exports, Chinese VA derives mainly from C29.



* Codes B06, B07 and C19–C30

Chart 2. Share of Chinese value added from selected sectors* in the gross exports of the V4 economies, 2015–2022
Source: own study based on OECD 2025a; 2025c.

Based on these results, it becomes evident that market size in Poland and Czechia is a key factor behind the relatively greater importance of Chinese VA in final demand. By contrast, a different pattern emerges when the focus shifts from domestic consumption to export performance. In the case of gross exports, Slovakia and Hungary function as FDI-led production hubs and thus appear more exposed to potential disruptions in the supply of Chinese VA. Greater reliance on Chinese components in key export sectors, particularly automotive and electronics, may help contextualise differences in V4 foreign-policy orientations and risk tolerance. It may also, at least in part, explain the stronger preference in Hungary and Slovakia for a balancing strategy between the EU and China. Under such circumstances, managing political tensions may be driven by national interests and the imperative to safeguard domestic employment and industrial performance.

This mapping of exposure also strengthens the rationale for locating potential dependence on China in the dual-use domain within categories associated with medium- and high-technology intensity, such as components, equipment, and machinery, while also acknowledging the salience of raw materials, particularly in Poland. Crucially, these observations are matched by an evident trend: the relatively high share of dual-use goods in V4 imports from China between 2015 and 2024 (Chart 3).

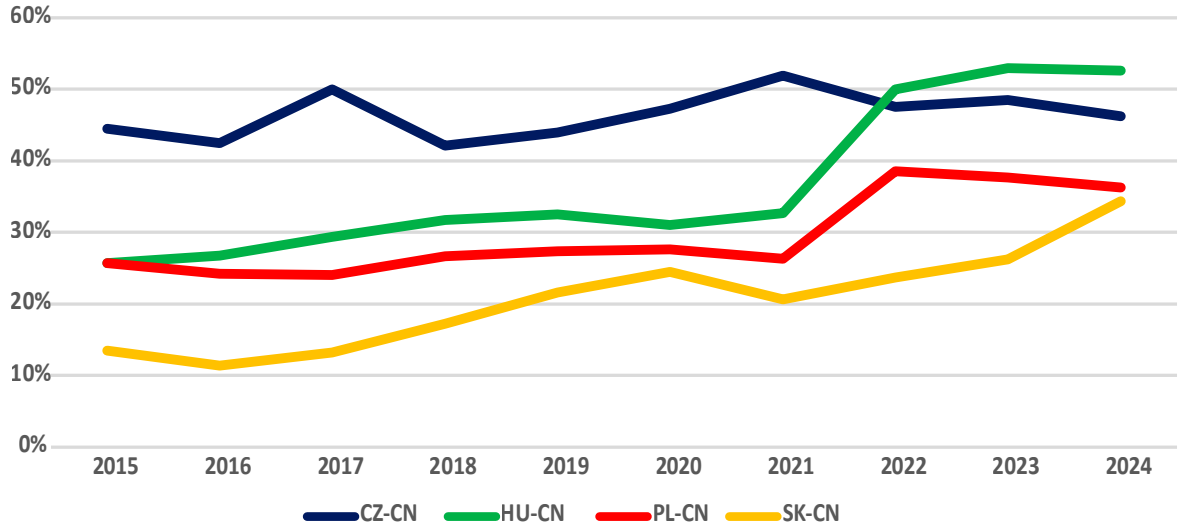


Chart 3. Share of dual-use goods in V4 imports from China, 2015–2024
Source: own study based on the ITC 2025 and the European Commission 2024.

Among the dual-use clusters, those accounting for the highest value of V4 imports from China are concentrated in the mechanical, electrical, and electronics industries. Thus far, the findings naturally lead to the question of whether the V4 economies possess competitive potential in the area of dual-use goods that could contribute to strengthening their economic resilience. To address this issue, two complementary approaches are proposed to identifying (dis)advantages. First, I employ a modified version of the symmetrical revealed comparative advantage indicator (SRCA*), defined as the difference between export- and import-based advantages ($SRCA^* = SRCA_{exp} - SRCA_{imp}$), calculated at the 6-digit level of trade data disaggregation. Second, I examine the intensity and structure of intra-industry trade, distinguishing between vertical and horizontal components, at the 8-digit level of disaggregation. Taken together, these approaches allow to capture both competitive positions and the qualitative features of trade specialisation.

The results of the SRCA* analysis for dual-use goods point to a rather pessimistic assessment of the V4's current competitive position. Between 2020 and 2024, only 20–30% of all dual-use product clusters exhibited a revealed advantage. When the analysis is restricted to medium- and high-technology groups, the share declines further to 15–25% of all 851 dual-use HS6 MT, MHT, and HT clusters (see Chart 4). Narrowing the focus even more to sectors that are key to the EU's competitiveness and strategic autonomy (i.e., defence, space, clean-tech, bio-tech, and med-tech) yields the most sobering result: only 2–5% of clusters demonstrate a competitive advantage. These findings underscore the structural constraints faced by the V4 economies in leveraging dual-use production as a source of resilience.

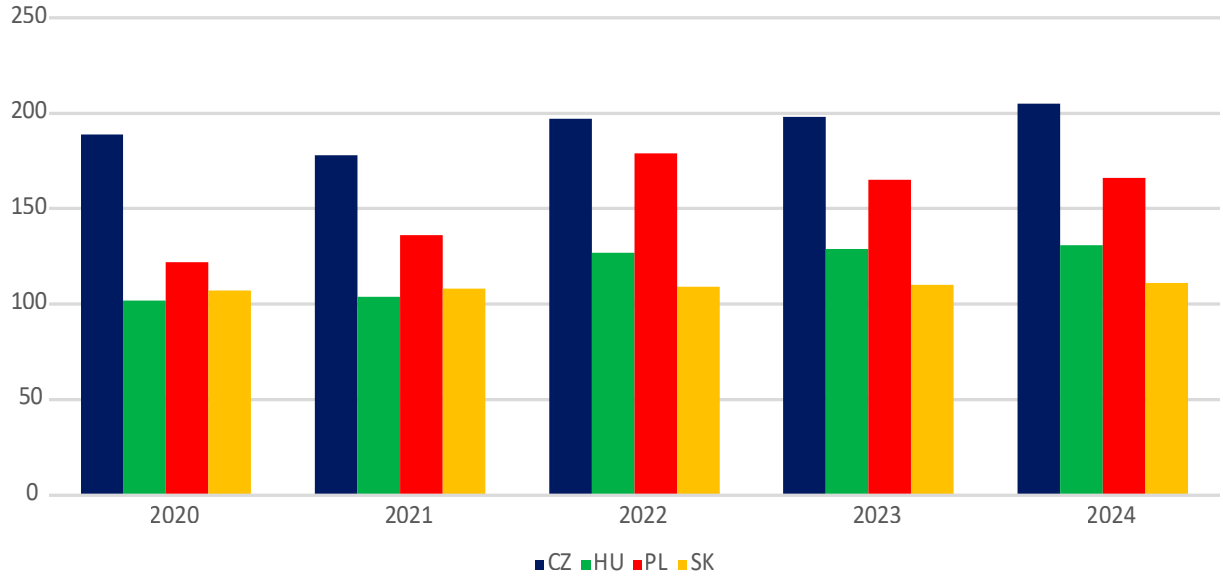


Chart 4. Number of dual-use HS6 clusters of medium- and high-technology intensity with a positive SRCA* in the V4 economies, 2020–2024
Source: own study based on the ITC 2025 and the European Commission 2024.

At the same time, however, country-specific dynamics suggest that external shocks can catalyse change and new opportunities for niche sectors. In the case of Czechia and Poland, the war in Ukraine has provided a significant impetus for transformations in selected segments of dual-use production and proven the capabilities of successful adaptation to external geopolitical circumstances. Among the clusters with the highest SRCA* values, there are drones, light aircraft, radio navigation equipment, firearms, howitzers, detonators, nitrocellulose, fuses, gunpowder stabilisers, and graphite electrodes. While these developments remain limited in scope, they shed light on areas in which demand and security rationales may intersect with emerging competitive potential.

Conversely, the dual-use clusters that appear most vulnerable to possible Chinese interference, i.e., those combining high turnover in total imports with the lowest value of the SRCA* index, include parts and accessories of automatic data-processing machines, electronic integrated circuits (CZ, HU), automatic portable data-processing machines, smartphones for wireless networks, parts suitable for use solely or principally with flat panel display modules (PL); and lithium-ion accumulators, and boards, cabinets, and similar combinations of apparatus for electric control (SK).

Taken together, this pattern suggests that advanced electronics and related components constitute the primary area of V4 vulnerability. This is particularly salient in the context of automation and robotisation, which increases the economy-wide relevance of such inputs not only for industrial production but also for everyday infrastructures and services. At the same time, the existing lack of competitive advantage in these segments should not provide justification for abandoning the development of domestic key competences. Instead, it highlights why capacity-building debates are central to economic security and strategic autonomy.

Building on this diagnosis, the next step in this study extends the analysis beyond trade values to incorporate quantities, as this enables us to estimate the intensity of intra-industry trade using the Grubel-Lloyd index (GLI). By comparing average export and import prices, I approximate product quality and distinguish

between vertical and horizontal trade. In combination, these measures provide a more detailed assessment of structural competitiveness in the V4's dual-use sectors.

The results (see Chart 5) indicate a relatively high level of structural competitiveness in the Czech economy (GLI > 70%), alongside a clear upward trend in the vertical high-quality trade category (i.e., exported goods are, on average, more expensive and thus proxied as higher quality than imported ones). A similar profile is also observed in Slovakia (GLI > 60%), where horizontal trade (i.e., comparable price/quality level in exports and imports) is more pronounced. By contrast, Hungary and Poland exhibit stagnation over the period covered by this study, with the GLI around 54–57%.

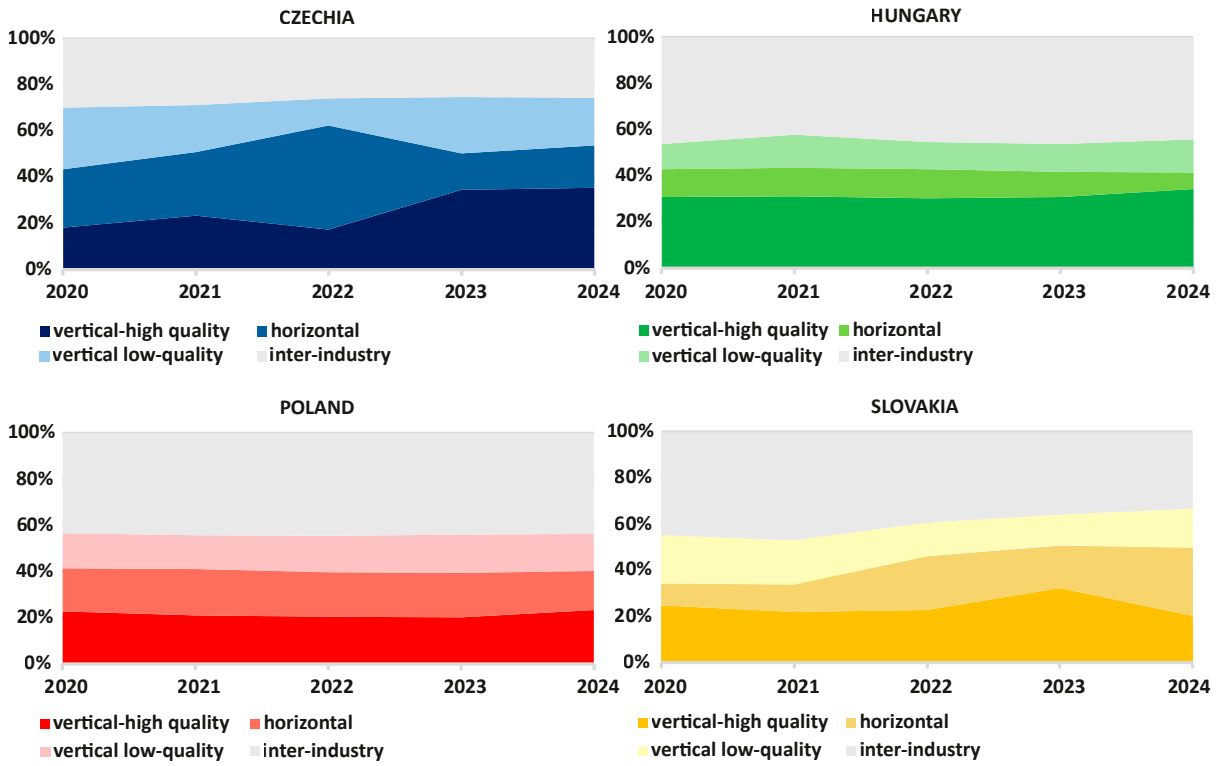


Chart 5. Intensity of intra-industry trade in dual-use goods of V4 economies, 2020–2024
Source: own study based on Eurostat 2025 and the European Commission 2024.

In identifying areas of heightened vulnerability, the analysis focuses on streams of vertical low-quality trade, where imported goods are of higher quality/value than exported products. This pattern signals likely constraints and asymmetric dependence. The results indicate that particular attention should be devoted to the machinery and electronics sectors. Across at least three V4 countries, recurrent categories include machines, mechanical appliances, and their parts, as well as electronic integrated circuits. Moreover, country-specific areas of potential vulnerability can also be identified. In Czechia, they include hard disk storage drives for automatic data-processing machines, industrial robots, and electrical apparatus for making connections to or in electrical circuits. In Hungary, vulnerability is concentrated in artificial graphite, while in Slovakia, it is found in machinery and apparatus for filtering or purifying air, apparatus for the transmission or reception of voice, images or other data, and cards incorporating one or more electronic integrated circuits.

Building on this analysis, the next stage of the study seeks to determine exposure to potential import disruptions from China through the diagnosis of strategic dependencies (SD),

following the methodology of the European Commission (2021). This approach combines three indicators: the import concentration index (the Herfindahl-Hirschmann index, HHI, with a benchmark threshold of 4000), the share of extra-EU-27 imports in total imports (threshold value of 0.5), and the ratio of extra-EU-27 imports to total exports (threshold value of 1.0). For the purpose of this analysis, I adopt a more conservative threshold of HHI = 2500 and focus on dual-use clusters in which China's share in imports exceeds 20%. This slight adjustment allows for a more sensitive identification of relevant dependencies.

The number of product clusters exhibiting strategic dependencies on China (see Chart 6) varies considerably across V4 economies. It is lowest in Slovakia and Czechia, and highest in Poland, where the number peaked at 75 clusters in 2022. In terms of persistent dependencies, Czechia recorded 7 clusters, Hungary 9, Poland 23, and Slovakia just 6. Once again, the common areas of exposure are concentrated in medium- and high-tech electronics, such as permanent magnets, parts suitable for flat panel display modules, lenses, prisms, mirrors, and other optical components, as well as organic chemistry, notably heterocyclic compounds with nitrogen hetero-atoms, which are critical to pharmaceutical production.

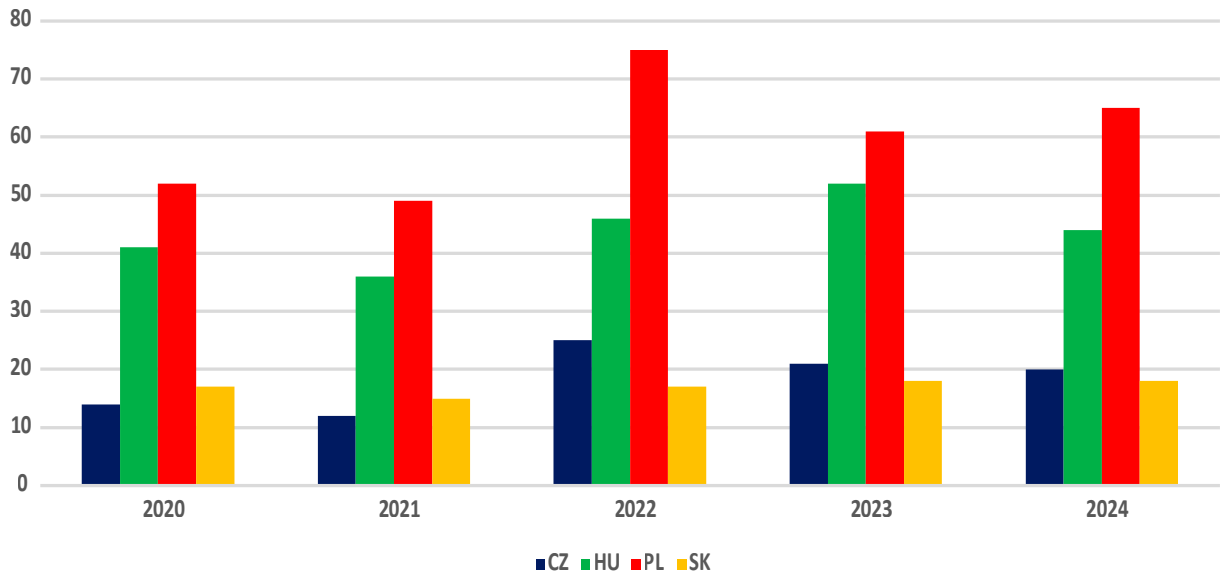


Chart 6. Number of dual-use HS6 clusters of strategic dependence on China in the V4 economies, 2020–2024
Source: own study based on Eurostat 2025 and the European Commission 2021; 2024.

From the perspective of the EU's strategic autonomy, these dependencies are most prevalent in the MT, MHT, and HT industries, as well as in the bio-tech sector. Taking into account the broader context of the green transition, additional vulnerabilities become apparent in components of energy-intensive industries. These vulnerabilities include diphenylamine and its derivatives, phosphides, germanium, and zirconium oxides, fluorosilicates, and imines and their derivatives. Such inputs are subsequently used in armaments production ranging from ammunition and rocket technologies to aircraft engines, radar systems, high-temperature protective coatings, military chemicals as well as in advanced electronics and optics, such as specialised semiconductors, optical fibres, LEDs, and lasers. This intersection of energy intensity,

technological sophistication and security importance highlights the systemic nature of dual-use dependencies.

Finally, I diagnose external vulnerabilities (EXVI) following the method of Garcia and Ho (2025). Conceptually, it partially synthesises the methods applied above by combining indicators of trade exposure with measures of international competitiveness. The assessment is thus organised around two dimensions: (1) exposure to supply disruptions, captured by import concentration (HHI) and the import-export ratio for a given commodity; and (2) competitive position in global markets captured by the classic RCA and price competitiveness approximated by the ratio of import and export prices. The EXVI ranges from 0 to 1 and is designed to identify dependencies ex post, i.e., on the basis of observed trade structures.

When assessing the V4 economies' vulnerability to imports from China using EXVI data for 2024, I focus only on clusters that meet three criteria: an EXVI value above the 95th percentile (critical vulnerability) or between the 80th and 95th percentiles (high vulnerability), and China's share of imports exceeding 20%. By doing so, there are 21 dual-use HS6 clusters for Czechia, 30 for Hungary, 42 for Poland, and 12 for Slovakia.

Discussion and Recommendations

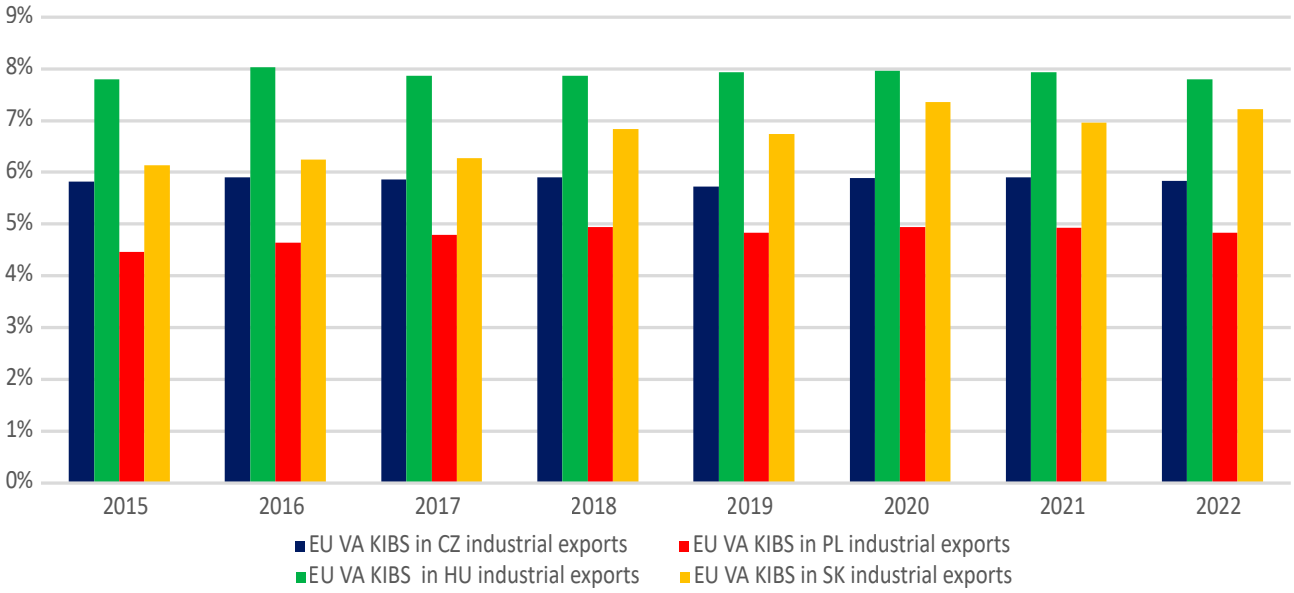
The results indicate that integration into GVCs has been accompanied by the V4 economies' growing dependence on Chinese VA, not only in final consumption, but also in gross exports, and, critically, in imported inputs. This reliance is relevant for sectors related to the digital and green transformations, as well as to the expansion of defence-production capacities. Against this background, the findings raise a fundamental question as to whether the EU's concept of open strategic autonomy represents a realistic approach to economic security policy or remains a mere normative postulate. Moreover, given the geopolitical configuration within the region, dependence on China may also serve as an indirect lever for Russia. Under these conditions, the weaponisation of asymmetries, especially in the domain of dual-use goods as a tool of economic statecraft, appears likely. Notably, European hydrogen and electromobility initiatives have not reduced dependence on Chinese components, while investments in battery factories and photovoltaic panels continue to rely on Chinese supplies (Stec 2025).

In such a context, policies that focus narrowly on innovation may prove unreliable and continue to leave societies exposed to unexpected consequences (see Winickoff and King 2025). Accordingly, debates on resilience mechanisms should extend beyond the integration of national risk audits (see Stec 2025) or the creation of additional frameworks such as the EU Critical Tech Observatory (see García-Herrero and Krystyanczuk 2025). The central challenge for the V4 economies lies in a misalignment of incentives, particularly those that entail short-term costs in resilience-building, thereby constraining the capacity to develop new solutions. Merely signalling desired changes through the proliferation of strategic documents has proven ineffective. An autonomous trajectory of technological development requires a more flexible policy and the ability to respond when a competitor, rival, or partner limits the available decision-making space. Finally, strengthening the competitiveness and resilience of the V4 economies depends

above all on innovative activity in the sectors most exposed to potential supply disruptions from China: automotive, mechanical, electronics, chemical, optical, and critical raw materials processing.

In this light, the effective pursuit of strategic autonomy requires a more nuanced understanding of what openness entails today. Therefore, I argue for stronger coordination of activities at the industry level. This could be achieved through the systematic exchange of experience and best practices during frequent meetings with industry associations, complemented by targeted facilitation and participation from representatives of public administration. This coordination would help reorient efforts towards "triple-A" supply chains: agile, adaptable, and aligned (OECD 2025a), thereby enhancing their flexibility and resilience. At the same time, calibrated preferences for the domestic production of high-tech components remain crucial. A demand-side impulse could mitigate the persistent problem of under-scaling within the EU (see García-Herrero and Krystyanczuk 2025; Guinea et al. 2025) and stimulate new R&D investments. In this sense, openness and selective industrial support should not be treated as mutually exclusive; rather, combining them would strengthen failing competitive potential in an increasingly contested geoeconomic environment. It is essential to recognise that China strives to deepen interdependencies via company-to-company partnerships to ensure that future restrictions carry more significant economic or political weight (see Pucek, Stoelinga, and Korteweg 2026; Shopov 2026).

Moreover, as industrial production becomes intertwined with the services, the V4 countries should improve the share of both domestic and European VA derived from the knowledge-intensive business services (KIBS) within their industrial exports (see Charts 7 and 8). This shift implies a stronger policy focus on embedding high-value services into manufacturing-based export models. In this context, programmes prioritising projects with high European VA could encourage investors to cooperate more closely with local suppliers of components and knowledge. This approach seems to be the logic underpinning the "Made in/with Europe" concept behind the Industrial Accelerator Act (European Commission 2026). Furthermore, consideration should also be given to the preferential use of a domestic VA criterion in public procurement and R&D spending. This can be combined with an assessment of supply-chain resilience, regional service capabilities, timely access to spare parts, and inventory-maintenance requirements. Further measures may integrate common V4 projects under the IPCEI framework, as well as tax incentives offering preferential rates for regional consortia developing intellectual property in the V4 countries. Finally, sectoral fast tracks tailored to firms in dual-use ecosystems that are central to V4 competitiveness and resilience would also be advisable.



* Excluding domestic VA.

Chart 7. Share of value added from the EU* from knowledge-intensive business services in the industrial exports of the V4 economies, 2015–2022
Source: own study based on OECD 2025a; 2025c.

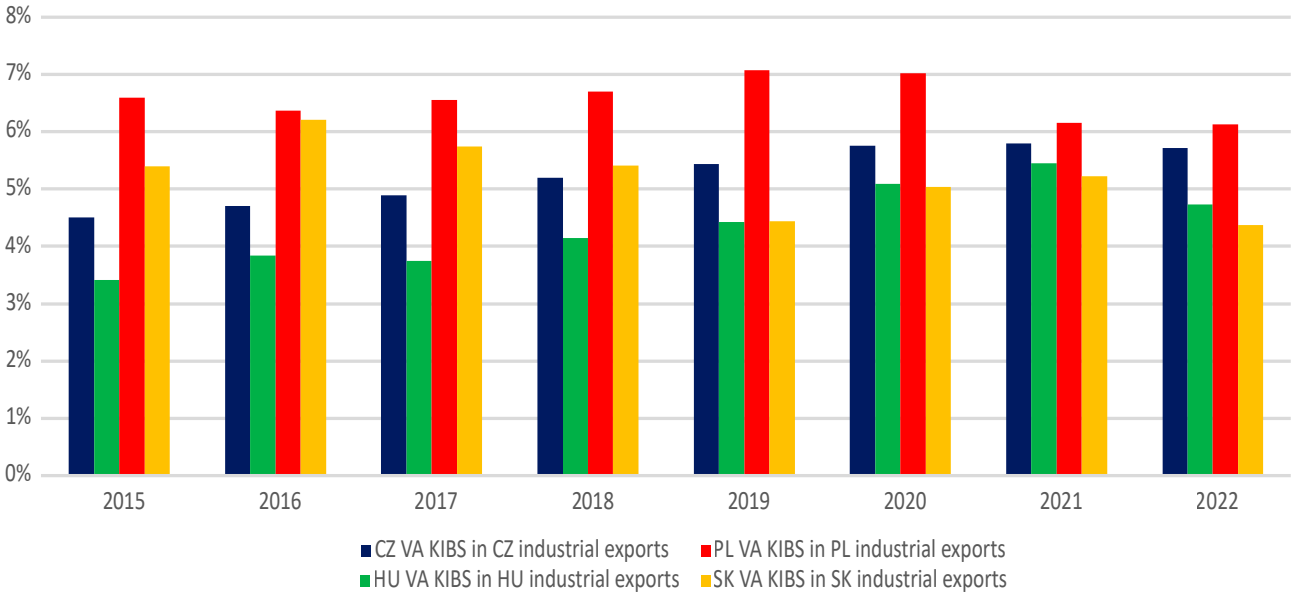


Chart 8. Share of domestic value-added from knowledge-intensive business services in the industrial exports of the V4 economies, 2015–2022
Source: own study based on OECD 2025a; 2025c.

At the same time, these proposals should be read against the inertia of production networks and the reality that GVC reconfiguration is inherently gradual. From the V4 perspective, the effectiveness of near- and friend-shoring as resilience-enhancing strategies will depend more on the quality of the "new playing field". This includes a disciplined selection of R&D priorities, financing for dual-use innovations (see Ferriani, Albori, and Ristuccia 2025) complemented with appropriate infrastructure, and sustained investments in technological capabilities. A key uncertainty

concerns the feasibility of substituting Chinese suppliers with producers from "friendly" countries, which would incur the loss of some intangible assets and contracts. Thus, these efforts may also require an information campaign that reshapes prevailing perceptions of China: no longer as a low-cost provider of high-tech goods, but as an actor influencing key links in supply chains.

Finally, the development of analytical tools remains the cornerstone of EU and V4 economic security policy. The identification of critical dependencies, extending beyond dual-use goods, has become more demanding because of the complexity of GVCs. Simple diversification is rarely sufficient on its own. What is needed is the systemic mapping of key nodes, potential chokepoints, and areas in which a loss of control would be unacceptable, thereby clarifying what must be done, where, how, and when. This applies both to the construction of complex scenarios of potential geoeconomic coercion and to the day-to-day, low-profile implementation of recommendations emerging from security and resilience audits. To this end, strengthening analytical capacity in international trade is essential at the intersection of customs authorities, economic intelligence, and policy-oriented research agencies to identify shifts in trade patterns, verify buyers, and screen targeted deliveries. At the same time, a common database would facilitate information-sharing in cases of suspicious transactions. Ultimately, the objective should be not only to respond to crises as they arise, but also to build and demonstrate the capacity to set the agenda.

Conclusion

The absence of decisive action in response to growing pressure from China risks entrenching the peripheral development model of the V4 economies. Trade tensions and uncertainty concerning the potential weaponisation of economic relations create an incentive to reassess development strategies. In particular, technological spillovers at the domestic, V4, and European levels need to be prioritised. Given the pace of technological change, especially as driven by artificial intelligence, the availability of human capital, intellectual resources, and R&D capacities in the automotive, electronics, mechanical engineering, chemical, optical, and defence sectors constitute a fundamental prerequisite for enhancing innovation potential. They enable the generation of unique value added in dual-use domains by encompassing both industrial activities and knowledge-intensive business services.

From a governance perspective, the monitoring of V4 resilience should integrate quantitative indicator analysis with the identification of critical nodes, and an assessment of regulatory practices. Attention should be paid to technical standards, licensing regimes, the physical availability of original components, and access to high-quality substitutes. This approach would imply a return to a more active industrial policy, a shared consensus on priority areas, and an appropriate scale of public support. This, in turn, underscores the significance of coordination and cooperation among the V4 countries themselves. At the EU level, forward-looking measures aimed at reducing the risk of unwanted know-how transfer such as the screening of trade flows and foreign investments represent an important, albeit still limited, component of the EU's economic security policy.

In this light, a central challenge for both the V4 and the EU is to regain agency namely, the capacity and political will to make autonomous choices under conditions of complex interdependence. A key dimension is developing a more accurate understanding of China's strategy towards the region,

including the prospect of consolidating its position in the supply of dual-use goods and the identification of alternatives. Indirect linkages among the V4 economies through GVCs and their embeddedness in the German industrial ecosystem also highlight the relevance of in-depth analyses, as these links may transmit tensions in less visible ways. Consequently, the fundamental issue for Czechia, Hungary, Poland, and Slovakia is how to balance the short-term gains associated with cooperation with China against a long-term approach centred on economic security and resilience. This trade-off cannot be assessed solely at the level of bilateral relations.

Acknowledgements

I am grateful to two anonymous referees, my academic colleague Andrzej Polus, and the participants in the conference "Global Economy at the Crossroads", held at the Warsaw School of Economics on 14 November 2025, where an earlier version of this paper was presented, for their valuable comments and insights. Furthermore, this research benefited from insights gained during my public service at the Polish Economic Institute. Any remaining errors or omissions are entirely my own.

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Comparative Economic Research. Central and Eastern Europe
Volume 29 Number 3, 2026
https://doi.org/10.18778/1508-2008.29.22

Energy Trade Reconfiguration in Central and Eastern Europe After the Russia–Ukraine War: Evidence From PPML and GAP Analysis

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Abstract

This article analyses how the energy-related foreign trade structure of Central and Eastern European (CEE) EU Member States has evolved since the Russia–Ukraine war. The study focuses on the diversification of import sources and the geographic reorientation of exports, using detailed HS27 data at the HS4 level for eleven CEE countries. The empirical approach combines a Poisson Pseudo-Maximum Likelihood gravity model with a Supply-Gap Replacement Analysis to identify which partners substituted for lost imports from Russia and Belarus. A new indicator Re-Export Potential is also introduced to capture potential intra-regional energy flows and emerging distribution hubs.

Funding information: This research was funded by the research project Potencjał Program, No. 027/EEE/2025/POT, administered by the Kraków University of Economics.
The percentage share of the Authors in the preparation of the work is: D.C.-M. – 25.00%, D.C. – 25.00%, S.G. – 25.00%, M.T. – 25.00%.
Conflicts of interests: None.
Ethical considerations: The Authors assure of no violations of publication ethics and take full responsibility for the content of the publication.
Received: 5.01.2026. Verified: 30.03.2026. Accepted: 24.06.2026

The findings show a reduction of more than 99% in direct HS27 imports from Russia and Belarus after 2022 and a major reshaping of supply patterns. Norway, the Gulf states, the United States and North Africa became the main substitutes, while several Western European states acted as key transit and refining hubs. In contrast, CEE countries achieved only limited reorientation of their energy exports, reflecting higher production costs and constrained adjustment capacity after the loss of Russian crude.
The Re-Export Potential results point to new regional energy corridors in the Adriatic, Baltic and Black Sea regions. Overall, the study shows that the transformation of CEE energy trade is structural and likely to persist, reshaping the region's role within Europe's energy supply chains.

Keywords: CEE energy trade, trade reorientation, PPML, supply-gap analysis, energy security, re-export potential, sanctions

JEL: C33, F14, F51, Q41, Q48

Introduction

The Russia–Ukraine war has become a major turning point for the European economy, with particularly strong effects on Central and Eastern Europe (CEE). Due to their geographical location and historical ties, CEE countries once maintained long, deep trade relations with Russia and Belarus. However, the introduction of sanctions, disruptions to traditional transport routes and new geopolitical risks forced a rapid restructuring of their external economic relations. The energy sector was affected most severely: sanctions effectively banned energy imports from Russia and Belarus, while soaring prices, higher transport costs and uncertainty over alternative suppliers further accelerated the need for adjustment.

Since mid-2025, the structural reorientation of Europe's energy supply has been further consolidated at the institutional level. With EU energy ministers deciding on 20 October 2025 to phase out imports of Russian oil and gas by 1 January 2028, and to refrain from concluding new long-term gas contracts from 2026 onwards, there is now a formal policy framework for the transformation process already observable since 2022 (Abnett 2025; Council of the European Union 2025a). This decision confirms a reduction in the dependence on Russian energy carriers that is visible in the empirical data, with Russia's share in EU gas imports falling to around 12 per cent and its share in oil imports to below 2 per cent by the first half of 2025 (Council of the European Union 2025b; Eurostat 2025; International Energy Agency 2025a).

At the same time, the most recent developments highlight the heterogeneous adjustment capacity within Europe: while most member states have been able to diversify their supply structures, several CEE countries – in particular Hungary and Slovakia – remain structurally tied to legacy pipeline infrastructures such as the Druzhba system and selected transit agreements (Levi et al. 2025). These persistent dependencies shape regional vulnerability during the transition phase and mark those states in which reorganisation processes proceed more slowly due to limited alternatives.

In light of these developments, it is likely that the tendencies observed since 2022 will continue to strengthen over the coming years. This is because the ongoing transformation of Europe's energy system is not merely reactive but structural in nature: it is anchored in new regulatory commitments, reinforced by investment decisions and supported by growing integration within the internal energy market. Increasing diversification of supply sources, the emergence of new distribution

hubs and persistent infrastructure constraints in parts of CEE all indicate that adjustment trajectories across the region will become increasingly differentiated, raising the importance of analysing the evolving patterns of energy-related trade flows.

In view of the above, this article examines how foreign trade patterns evolved after 2022 in eleven CEE EU member states, with a particular focus on energy products (HS27). By analysing both imports and exports, the study captures two complementary dimensions: the reorientation of energy supply sources and the shifts in export destinations for energy-related goods. Based on theory and prior findings, two hypotheses are proposed: **(H1)** the geopolitical shock of 2022 led to a structural reallocation of CEE HS27 imports away from Russia and Belarus; **(H2)** sanctions and supply disruptions caused a sharp decline in CEE HS27 exports to Russia and Belarus, with only a limited redirection of outflows to other markets.

The empirical approach combines the Poisson Pseudo-Maximum Likelihood (PPML) gravity model with a Supply Gap Replacement Analysis (GAP), which tracks changes in CEE import and export structures after 2022. To capture intra-regional dynamics and the emergence of distribution hubs, a new indicator Re-Export Potential (RP) is introduced, linking the PPML and GAP perspectives. Overall, the study contributes to the debate on how the war has reshaped trade patterns, energy security and the resilience of CEE economies.

Literature Review

The economic repercussions of the war in Ukraine have been widely analysed, generating both preliminary assessments and more extensive studies. Early contributions highlight its severe and lasting effects on global commerce, including supply and price shocks in commodity markets and major disruptions to supply chains (Roubini 2022; World Bank 2022). Researchers also note that the magnitude of these shocks depends heavily on countries' capacity to diversify suppliers (Borin et al. 2022), while forecasts predict that global trade may decline by around 1% (Ruta 2022). Given the key role of Russia and Ukraine as suppliers of energy and industrial commodities such as oil, natural gas, wheat, neon, titanium and palladium the conflict has generated substantial turbulence in global markets (Cohen and Ewing 2022; Mbah and Wasum 2022; Wiseman 2022). The blockade of Ukrainian exports and sanctions against Russia have reshaped trade in non-precious metals, energy, minerals and agricultural goods (Bentley et al. 2022). According to the United Nations (2022), the war has disrupted not only energy and food markets but also global financial systems, exacerbated by persistent supply bottlenecks and rising transport costs.

These findings are consistent with Zhou et al. (2023), who show that the conflict has induced cascading failures in global energy and food trade networks, producing price spikes and heightening the vulnerability of import-dependent states.

A growing strand of research examines the conflict through bilateral and multilateral trade flows. Evidence indicates that sanctions and reduced access to energy commodities particularly affect Europe, whose dependence on Russian and Ukrainian imports exceeds that of other major economies (Bhattarai, Romm, and Siegel 2022; International Monetary Fund 2022). Furthermore, Hallová, Savov,

and Horská (2024) document disruptions in EU agricultural trade, driven by heightened market volatility and policy changes. Using an Autoregressive Distributed Lag (ARDL) framework, they demonstrate that geopolitical risk strongly affects agricultural prices, thereby prompting the EU to seek alternative suppliers and strengthen domestic production.

A substantial part of the literature underscores that CEE countries are among the most vulnerable, particularly those with strong pre-war ties to Russia. Their exposure stems from geographical proximity and a trade structure in which Russia's share exceeds the EU average (Prohorovs 2022). For instance, the Baltic States were among the first to experience the effects of declining trade and rising energy prices (Noack and Brady 2022). Meanwhile, Korosteleva (2022) argues that Poland, Czechia, Hungary, Slovakia and Bulgaria need to diversify energy imports, despite substantial economic and logistical constraints.

Expanding the scope of analysis, Kulikova and Sinitsina (2023) analyse how geopolitical instability reshapes CEE trade relations with Russia, showing that sanctions and the energy shock disrupt economic ties, including through rerouting attempts to bypass restrictions. Further insights are provided by Kos-Łabedowicz and Talar (2024), who apply the Trade Vulnerability Index (TVI) to assess CEE resilience to wartime disruptions. Their results indicate considerable initial resilience, though vulnerabilities increased in the Baltic States and Poland in 2023. Crucially, they find no clear correlation between trade vulnerability and resilience to shocks.

Given Ukraine's role as a major exporter of agricultural and industrial goods, several studies analyse the conflict's impact on global agri-food and resource markets (Bułkowska and Bazhenova 2023; Aizenman et al. 2024). Habova (2024) situates these developments within a broader geopolitical context, arguing that intensified great-power rivalry most notably the Russia–Ukraine conflict constrains prospects for deeper CEE trade cooperation with China.

Regarding the assessment of trade flows, it is important to note that the European gas and liquefied natural gas (LNG) market has stabilised further since 2024. Price convergence between pipeline gas and LNG, together with expanded infrastructure and the growing role of LNG terminals in Northern and Central Europe, has strengthened internal market integration (Agency for the Cooperation of Energy Regulators 2025; International Energy Agency 2025, recent policy and analytical reports highlight increasingly interconnected and diversified supply chains (Council of the European Union 2025b; Levi et al. 2025). At the same time, they indicate that regional re-export dynamics especially through major EU distribution hubs remain shaped by political decisions, logistical constraints and persistent cross-country differences (Bartha 2025).

Nevertheless, although the literature offers valuable insights into the early effects of the war on CEE economies, important gaps remain. Many studies focus only on the initial phase of the conflict or rely on short time spans, and few provide detailed, geographically comprehensive analyses. As a result, to better understand the magnitude and nature of these ongoing changes, a closer examination of CEE trade relations with key partners is required. This study helps fill this gap by analysing developments in the energy sector.

Research Contribution

This study makes several important contributions to the literature on wartime trade disruptions and post-shock realignment. First, it looks at trade flows from 2017 to 2024 to give a medium-term view of the Russia–Ukraine war. This is in contrast to the short observation windows used in most existing research. This extended timeframe facilitates the differentiation between the initial shock phase and the ensuing restructuring dynamics, encompassing the gradual replacement of suppliers and the development of novel regional trade patterns.

Second, the analysis is performed at a more advanced level of data disaggregation than is typical in the literature. Most studies use 2-digit or sectoral statistics, but this work examines HS27 energy products at the HS4 level using bilateral flows. This method makes it possible to find product-specific substitution pathways and shows differences that would be missed with more general classifications, especially in fuel oils, coal, and gas-derived condensates.

Third, the paper presents an innovative two-step empirical design that connects identification and descriptive mapping. The gravity model estimated through PPML measures the size of trade reallocation caused by sanctions and supply shocks after 2022. The Supply-Gap Replacement (GAP) analysis, on the other hand, describes the size and direction of partner substitution. This combination lets us tell the difference between statistical proof of trade reorientation and its real-world effects on import and export volumes.

Fourth, we add the Re-Export Potential (RP) indicator to these methods. This indicator shows the physical limits of moving goods around within CEE. Current research primarily examines external trade partners or composite indices of vulnerability and resilience; conversely, the RP approach illustrates that the region's ability to absorb and redistribute energy supplies is simultaneously limited by the availability of imports and the demand for exports. This gives a more structural view of trade patterns after the war than accounts that only look at prices or policies.

Lastly, the paper looks at CEE energy trade from both the import and export points of view. The literature has recorded the decline of Russian energy imports; however, there has been insufficient focus on the redirection of CEE energy exports in the absence of pre-war downstream markets. By looking at these two pressures, we show that import substitution and export reallocation follow different paths of adjustment, which are affected by the availability of alternative markets, transportation capacity, and refinery feedstock constraints.

Research Methodology

The empirical analysis relies on a gravity model using the PPML estimator, now standard in empirical trade research (Santos Silva and Tenreyro 2006; 2011; Steinbach 2023). The model is applied to bilateral trade flows between CEE EU Member States and all trading partners, using HS27 and HS4 product-category data. The dependent variable measures the annual value of bilateral trade in each product (t).

The specification includes a sanctions indicator that identifies trade with Russia and Belarus after the introduction of sectoral restrictions, as well as global energy price variables (oil, gas, coal) matched to product categories through product-specific price indices. Standard errors are clustered at the CEE partner-country level, consistent with the fixed-effects structure and PPML's statistical properties.

Limited post-2022 variation in some country–product pairs and singularity issues prevented estimation of a fully saturated fixed-effects model (with exporter–year, importer–year, country-pair and product–year fixed effects). Thus, we employ an empirically feasible but fully identifiable design that includes a fixed effect for the CEE Member State – on the importing side (variant A) or exporting side (variant B) and a year fixed effect. This structure controls for all time-invariant characteristics of CEE economies and captures global shocks affecting energy trade.

The use of PPML mitigates heteroskedasticity concerns, accommodates zero trade flows, and preserves the log-level interpretation of coefficients, whereby the estimated parameters (β) can be interpreted as approximate percentage changes in trade values. Following Santos Silva and Tenreyro (2006), the estimated coefficients are interpreted as semi-elasticities, with exp(β) – 1 providing an approximate percentage change in trade flows. The empirical model is represented by the following equation (1):

$$\begin{aligned}\mathrm{Trade}_{\mathrm{ijkt}} = \exp(&\beta_1 \mathrm{Sanction}_{\mathrm{ijkt}} + \beta_{\mathrm{Br}} \mathrm{Brent}_{\mathrm{t}} \times 1\{\mathrm{k} \in \{2709, 2710\}\} \\ &+ \beta_{\mathrm{Gas}} \mathrm{TTF}_{\mathrm{t}} \times 1\{\mathrm{k} = 2711\} + \beta_{\mathrm{Coal}} \mathrm{Coal}_{\mathrm{t}} \times 1\{\mathrm{k} = 2701\} \\ &+ \mathrm{FE}_{\mathrm{side}} + \mu_{\mathrm{t}}),\end{aligned} \tag{1}$$

where:

Trade_{ijkt} – the value of the trade flow (variant A/B) between country (*i*) and its trading partner (*j*), for product (*k*[1]) (HS27) in year (*t*) (data source: United Nations Comtrade 2025); two equation variants are employed:

- **variant A:** the importer (*j*) is a CEE country, while the exporter (*i*) is an external partner;
- **variant B:** the exporter (*i*) is a CEE country, while the importer (*j*) is the trading partner;

$\mathrm{Sanction}_{ijkt}$ – a binary variable equal to 1 if product (*k*) (HS27) is traded with Russia or Belarus in year (*t*) (on the export side in variant A and on the import side in variant B) and is included in the list of goods subject to sectoral sanctions from the year of their introduction; 0 otherwise;

$\mathrm{Brent}_t \times 1\{k \in (2709,2710)\}$ – the Brent crude oil price index assigned to HS2709 (crude oil) and HS2710 (refined petroleum products) (data source: World Bank, 2025a, via FRED);

$\mathrm{TTF}_t \times 1\{k = 2711\}$– the natural gas price index for HS2711 (natural gas) (data source: World Bank 2025b, via FRED);

$\mathrm{Coal}_t \times 1\{k = 2701\}$ – the coal price index applied to HS2701 (coal) (data source: World Bank 2025c, via FRED);

1 Only HS codes 2701 and 2709–2711 are included in the analysis, as these categories are directly linked to Brent, TTF and Coal price indices. The remaining HS27 subheadings (2712–2716) are excluded due to their marginal share in total imports – collectively accounting for between 0.45% and 2.91% of total HS27 imports across the eleven CEE countries in the sample (average: approximately 1.7%; United Nations Comtrade 2025) – and the absence of a clear relationship with global fossil fuel markets (Authors' note).

FE_{side} – a fixed effect controlling for the CEE country; its form depends on the estimation variant ((*j*) in variant A and (*i*) in variant B);
μ_t – a year fixed effect controlling for global shocks and time trends affecting energy trade (e.g., global energy price cycles, broad macroeconomic conditions).

To complement the PPML results and to identify how the geographical structure of CEE imports and exports has evolved since 2022, an additional original procedure Supply-Gap Replacement Analysis is employed. The conceptual design of the GAP analysis is consistent with recent approaches in the literature on trade diversion and supply-shock substitution, where *pre*- and *post*-sanctions trade structures are compared to identify new trading partners (Wang and Hannan 2023; Darvas, Léry Moffat, and McCaffrey 2024). The objective of the method is to determine which countries replaced the lost energy imports from Russia and Belarus, and to which destinations CEE countries redirected their energy exports.

The procedure divides the sample into two periods: a *pre*-war phase, characterised by stable energy trade (2017–2021), and a *post*-war phase, marked by sanctions and diversification efforts (2022–2024). This approach is fully consistent with the logic of both PPML variants, as it relies on the same bilateral structure i–j: in the import analysis, this corresponds to variant A, whereas in the export analysis, it corresponds to variant B. The GAP analysis is conducted separately for each trading partner (country/region), using the following configurations:

- Variant A: the importer is a CEE country (j∈CEE), and the trading partner (*g*) acts as the exporter (*i* = *g*), excluding Russia and Belarus; HS4 ∈ {2701, 2709, 2710, 2711}.
- Variant B: the exporter is a CEE country (i∈CEE), and the trading partner (*g*) acts as the importer (*j* = *g*), excluding Russia and Belarus; HS4 ∈ {2701, 2709, 2710, 2711}.

For each trading partner (*g*), the total volume of trade in the *pre*-war (2; 4) and *post*-war (3; 5) periods is calculated using data from the United Nations Comtrade database (2025):

$$\mathrm{Im}_g^{\mathrm{pre}} = \sum_{j \in \mathrm{CEE}} \sum_{i=g} \mathrm{Imports}_{ij,HS27,2017-2021}, \tag{2}$$

$$\mathrm{Im}_g^{\mathrm{post}} = \sum_{\mathrm{j} \in \mathrm{CEE}} \sum_{\mathrm{i=g}} \mathrm{Imports}_{ij,HS27,2022-2024}, \tag{3}$$

$$X_g^{\mathrm{pre}} = \sum_{i \in \mathrm{CEE}} \sum_{j=g} \mathrm{Exports}_{ij,HS27,2017-2021}, \tag{4}$$

$$X_g^{\mathrm{post}} = \sum_{i \in \mathrm{CEE}} \sum_{j=g} \mathrm{Exports}_{ij,HS27,2022-2024}, \tag{5}$$

where:
$\mathrm{Im}_g^{\mathrm{pre}}$ – the total value of HS27 imports from partner (*g*) to all CEE in the period (2017–2021);
$\mathrm{Im}_g^{\mathrm{post}}$ – the total value of HS27 imports from partner (*g*) to all CEE in the period (2022–2024);
X_g^{pre}– the total value of HS27 exports from CEE to partner (g) in the period (2017–2021);
X_g^{post}– the total value of HS27 exports from CEE to partner (*g*) in the period (2022–2024).

Changes in imports (6; 7) and exports (8; 9):

$$\Delta\,\mathrm{Im}_g = \mathrm{Im}_g^{\mathrm{post}} - \mathrm{Im}_g^{\mathrm{pre}}, \tag{6}$$

$$\Delta \mathrm{Im}_g\% = \left(\Delta \mathrm{Im}_g / \mathrm{Im}_g^{\mathrm{pre}}\right) 100\%, \tag{7}$$

$$\Delta X_g = X_g^{\mathrm{post}} - X_g^{\mathrm{pre}}, \tag{8}$$

$$\Delta X_g\% = \left(\Delta X_g / X_g^{\mathrm{pre}}\right) 100\,\%, \tag{9}$$

where:
$\Delta \mathrm{Im}_g$ and ΔX_g – the absolute change in imports and exports, calculated as the difference between *post*-war and *pre*-war trade values;
$\Delta \mathrm{Im}_g\%$ and $\Delta X_g\%$ – the percentage change in imports and exports, calculated relative to *pre*-war trade values.

The use of cumulative sums rather than averages is consistent with the logic of the GAP analysis, whose purpose is to reconstruct the actual magnitude of the supply gap created by the loss of Russian and Belarusian energy deliveries. This gap is quantitative in nature and refers to missing physical volumes; therefore, comparing the total import and export volumes in the *pre*- and *post*-war periods makes it possible to identify which countries effectively replaced the lost supply, and to what extent. The sum of values also allows us to distinguish ordinary economic growth from genuine structural realignments in the geography of trade.

The differing lengths of the *pre*- and *post*-war periods reflect the adoption of the same time horizon used in the PPML gravity models, ensuring methodological consistency across approaches. In this way, the GAP analysis complements the PPML estimations: it separates temporary price-driven effects from persistent structural adjustments and identifies the real substitutes for Russian and Belarusian energy flows. Together, both methods provide a comprehensive and robust picture of post-2022 adjustments in CEE energy supply chains. It should be emphasised that GAP is a descriptive tool: it measures changes in observed trade flows and does not identify causal substitution effects.

To complement the PPML gravity models and the GAP analysis, an additional analytical tool the RP indicator is introduced to capture intra-regional energy flows in CEE that may have arisen due to the abrupt redirection of supply sources after 2022. Such flows are not directly observable in the PPML framework, which focuses on trade volumes and price effects, nor in the GAP analysis, which examines shifts in import patterns. Therefore, the RP indicator serves as a complementary instrument that enables a reconstruction of the potential redistribution of energy products within CEE.

The RP indicator is a simple but conservative measure of the maximum physically plausible scale of flows that could take the form of intra-CEE re-exports. Because it relies on official import and export statistics, it cannot precisely identify movements resulting from fuel mixing, refinery blending, or transit shipments recorded differently across customs systems. RP should, therefore, be interpreted as a potential measure rather than an estimate of realised re-exports – an upper bound of possible intra-CEE flows rather than a direct measure of physical movements. This approach helps assess whether a given CEE country could have acted as a trading hub for HS27 products.

The indicator uses a minimum operator, reflecting physical constraints on commodity flows: no country can re-export more than it imports from non-CEE suppliers (supply constraint) or more than it exports

to CEE partners (demand constraint). This construction is consistent with flow-accounting logic in analyses of energy transit and supply-chain routing, where indirect flows are bounded by available imports or maximum onward exports (Lahr 2005; Singh and Eisenmenger 2010; Dietzenbacher et al. 2013; Los, Timmer, and de Vries 2016).

$$\mathrm{RP}_{i,t} = \min\left(\mathrm{Im}_{i,t}^{\mathrm{nonCEE}}, X_{i,t}^{\mathrm{CEE}}\right), \tag{10}$$

$$\mathrm{Im}_{i,t}^{\mathrm{nonCEE}} = \sum_{j \notin \mathrm{CEE}} \mathrm{trade\_value}_{j,i,t}, \tag{11}$$

$$\mathrm{X}_{i,t}^{CEE} = \sum_{j \in CEE, j \neq i} trade\_value_{i,j,t}, \tag{12}$$

where:

$\mathrm{RP}_{i,t}$ – the potential re-export of energy products by country (*i*) in year (*t*);

min (•) – a logical operator indicating that the potential re-export ($\mathrm{RP}_{i,t}$) is simultaneously constrained by the volume of available imports from outside the CEE region and by the volume of exports to other CEE countries;

$\mathrm{Im}_{i,t}^{\mathrm{nonCEE}}$ – the value of HS27 energy imports of country (*i*) from non-CEE partners in year (*t*);

$X_{i,t}^{\mathrm{CEE}}$ – the value of HS27 energy exports from country (*i*) to other CEE countries in year (*t*).

For any variable $\mathrm{Z}_{i,t} \in \left\{Im_{i,t}^{nonCEE}, X_{i,t}^{\mathrm{CEE}}, \mathrm{RP}_{i,t}\right\}$, average annual changes were calculated for the *pre*-war period (2017–2021) and the *post*-war period (2022–2024). To ensure comparability between periods of unequal length, variable values were expressed as annual averages. Accordingly, (T_{pre})denotes the number of years in the pre-2022 period, while (T_{post}) denotes the number of years in the post-2022 period. The average annual value of variable ($Z_{i,t}$)was therefore computed as (13; 14):

$$\mathrm{Z}_i^{pre} = (1/\mathrm{T}_{pre}) \sum_{t \in pre} \mathrm{Z}_{i,t}, \tag{13}$$

$$\mathrm{Z}_i^{post} = (1/\mathrm{T}_{post}) \sum_{t \in post} \mathrm{Z}_{i,t}. \tag{14}$$

The level change (15) and the percentage change (16) of indicator (Z_i) were then defined as:

$$\Delta Z_i = Z_i^{\mathrm{post}} - Z_i^{\mathrm{pre}}, \tag{15}$$

$$\Delta Z_i^{(\%)} = \left[\frac{Z_i^{\mathrm{post}} - Z_i^{\mathrm{pre}}}{Z_i^{\mathrm{pre}}}\right] \times 100\% \quad \left(\text{undefined if } Z_i^{\mathrm{pre}} = 0\right). \tag{16}$$

This construction reflects the economic logic of energy distribution within the CEE region: a country cannot act as an intermediary to a greater extent than allowed by its import position and its capacity to export within the region. Consequently, the RP indicator functions as a measure of regional hub potential, enabling the identification of economies that may have played a central role in redistributing energy commodities. It also provides insight into the extent to which intra-regional supply chains were reconfigured following the loss of Russian and Belarusian supplies.

Empirical Results

Table 1 presents the PPML estimation results for the import of energy products (HS27) to CEE countries (model variant A). The most important finding concerns the impact of EU sanctions imposed on Russia and Belarus from 2022 onwards. Specifically, the coefficient on the *Sanction* variable is strongly negative and highly statistically significant (β = –5.0872, $p < 0.001$). In the log-linear interpretation of the PPML model, this corresponds to a reduction in import flows of approximately 99.4%. This indicates that the introduction of sectoral sanctions led to an almost complete cessation of energy trade between CEE countries and the sanctioned partners. Consequently, these findings provide clear empirical evidence of the abrupt collapse of energy imports from Russia and Belarus after 2022.

Table 1. PPML gravity model estimates for import flows of energy products (HS27) – model variant A (CEE as importers)

Variable	Coefficient	Std. Error	Z-stat	p-value	95% CI (lower)	95% CI (upper)
Constant	17.4653***	0.237	73.731	0.000	17.001	17.930
Sanction_{ijkt}	−5.0872***	0.390	−13.060	0.000	−5.851	−4.324
$\text{Brent}_t \cdot 1\{k \in \{2709, 2710\}\}$	0.0166***	0.003	5.698	0.000	0.011	0.022
$\text{TTF}_t \cdot 1\{k = 2711\}$	0.0538***	0.013	4.284	0.000	0.029	0.078
$\text{Coal}_t \cdot 1\{k = 2701\}$	0.0007	0.002	0.447	0.655	−0.002	0.004
Country FE: Croatia	−0.0841	0.197	−0.428	0.669	−0.469	0.301
Country FE: Czechia	0.4584**	0.191	2.394	0.017	0.083	0.834
Country FE: Estonia	−0.9374***	0.219	−4.284	0.000	−1.366	−0.509
Country FE: Hungary	0.5554***	0.195	2.848	0.004	0.173	0.938
Country FE: Latvia	0.7086***	0.223	3.173	0.002	1.146	0.271
Country FE: Lithuania	0.4887**	0.208	2.355	0.019	0.082	0.896
Country FE: Poland	1.1829***	0.193	6.139	0.000	0.805	1.560
Country FE: Romania	0.2709	0.194	1.397	0.162	−0.109	0.651
Country FE: Slovakia	0.2359	0.196	1.202	0.229	−0.149	0.621
Country FE: Slovenia	−0.3958*	0.221	−1.790	0.073	−0.829	0.038
Year FE: 2018	−0.0398	0.209	−0.190	0.849	−0.450	0.371
Year FE: 2019	0.0140	0.203	0.069	0.945	−0.383	0.411
Year FE: 2020	−0.1460	0.207	−0.706	0.480	−0.551	0.259
Year FE: 2021	−0.1565	0.207	−0.755	0.450	−0.563	0.250

Variable	Coefficient	Std. Error	Z-stat	p-value	95% CI (lower)	95% CI (upper)
Year FE: 2022	− 0.2034	0.298	− 0.683	0.494	− 0.787	0.380
Year FE: 2023	− 0.0104	0.214	− 0.049	0.961	− 0.430	0.409
Year FE: 2024	− 0.0790	0.208	− 0.380	0.704	− 0.486	0.328

Notes: ***, **, and * indicate significant at the 1%, 5% and 10% levels, respectively. Bulgaria serves as the reference category for the country fixed effects; its coefficient is absorbed by the model intercept. Model fit: $N = 9{,}298$; $df = 21$; Log-Likelihood = -2.9199×10^{12}; Deviance = 5.8397×10^{12}; Pearson $\chi^2 = 1.84 \times 10^{13}$; Pseudo $R^2 = 1.000$.

Source: authors' calculations.

Energy price indices also have a statistically significant effect on import volumes. Higher Brent crude prices are associated with increased imports of crude oil and refined petroleum products (HS2709–2710), with the coefficient of 0.0166 ($p < 0.001$) indicating that a one-unit rise in the Brent index raises imports by roughly 1.7%. A comparable pattern emerges for natural gas (TTF, HS2711): the coefficient of 0.0538 ($p < 0.001$) implies that a one-unit increase in the gas price index boosts imports by about 5.5%. These results reflect limited short-run demand elasticity in CEE, where supply-security needs especially during mandatory storage-filling periods override short-term price responsiveness. By contrast, the coal price index (HS2701) is not statistically significant, suggesting no measurable price sensitivity in coal imports during the period studied.

The country fixed effects confirm substantial structural heterogeneity within the CEE region. Specifically, Poland, Latvia, Hungary, Lithuania and Czechia display significantly positive fixed effects, reflecting persistently higher import levels driven by industrial demand, economic scale and their roles in regional energy markets. In contrast, Estonia and Slovenia exhibit negative fixed effects, indicating structurally lower import needs. This highlights the importance of accounting for country-specific characteristics to obtain reliable estimates.

The year fixed effects are statistically insignificant, suggesting that once sanctions and global energy prices are included, no additional time-specific shocks influence HS27 import flows. Thus, post-2022 changes are primarily driven by sanctions and global price dynamics rather than broader temporal trends.

Overall, the results show that the geopolitical shock of 2022 and the EU sanctions regime fundamentally reshaped CEE energy imports, confirming both the collapse of trade with sanctioned suppliers and the region's continued sensitivity to global energy prices. The positive fixed effects for Hungary and, to a lesser extent, Slovakia, capture their overall dependence on energy imports; however, external evidence indicates that both countries remain disproportionately reliant on Russian supplies a pattern not fully identifiable within the PPML framework (Sabadus 2025).

Table 2 summarizes the GAP analysis (variant A), illustrating changes in CEE energy imports (HS27) after 2022 and identifying the main suppliers that expanded deliveries to the region. These increases reflect both direct substitution for Russian inputs and the growing importance of European energy hubs whose additional imports largely represent re-export activity.

Table 2. GAP analysis results for energy imports (HS27) to CEE countries – variant A

Partner country/region	Pre-2022 (USD billion)	Post-2022 (USD billion)	Δ Change (USD billion)	Δ Change (%)
Norway	2.9409	27.1699	24.2289	823.9
Gulf countries	9.3599	34.9368	25.5769	273.3
USA	6.0170	21.1688	15.1518	251.8
North Africa	1.0562	3.1992	2.1430	202.9
Netherlands	1.4025	3.6981	2.2957	163.7
UK	1.8576	4.7789	2.9213	157.3
Belgium	1.3155	2.4135	1.0971	83.5
Italy	5.5599	8.4341	2.8742	51.7
Germany	12.1998	18.0890	5.8892	48.3
France	0.7333	0.8228	0.0895	12.2

Notes: Gulf includes Saudi Arabia, the United Arab Emirates, Qatar, Kuwait, Oman and Bahrain. North Africa includes Algeria and Libya.
Source: authors' calculations.

The results clearly confirm a substantial reorientation of energy imports in CEE countries after 2022. The strongest substitution effect is observed for Norway, whose deliveries increased more than eightfold (to over USD 27 billion), making it the principal supplier of pipeline gas to the region. Gulf countries expanded their exports to CEE by more than USD 25 billion, becoming the key replacement for Russian crude oil particularly for refineries in Poland, Lithuania, and Romania. The United States recorded an increase of approximately USD 15 billion, strengthening its position as the dominant supplier of LNG to regional terminals, such as Świnoujście in Poland and Krk in Croatia.

The results also point to a significant rise in trade flows between CEE countries and selected Western European economies after 2022, reflecting the redirection of energy supply routes following the interruption of imports from Russia and Belarus. The largest increases are associated with countries that function as major European energy hubs through which "new molecules" of gas, oil, and LNG originating mainly from the United States, Norway, Qatar, and North African exporters entered the EU market.

The principal distribution nodes include the Netherlands (the Port of Rotterdam and the Gate LNG terminal), Belgium (the Zeebrugge terminal), Italy, and France, all of which played a central role in receiving, regasifying, and forwarding these supplies towards CEE markets. For example, imports from the Netherlands increased by over 160%, reflecting its role as a hub for LNG and refined petroleum products. The United Kingdom and Germany also partially fulfilled similar functions, acting as intermediaries in transit and blending operations.

Overall, the findings indicate a profound restructuring of the geographic composition of energy imports, marked by a decisive shift away from Russia towards a diversified network of global suppliers

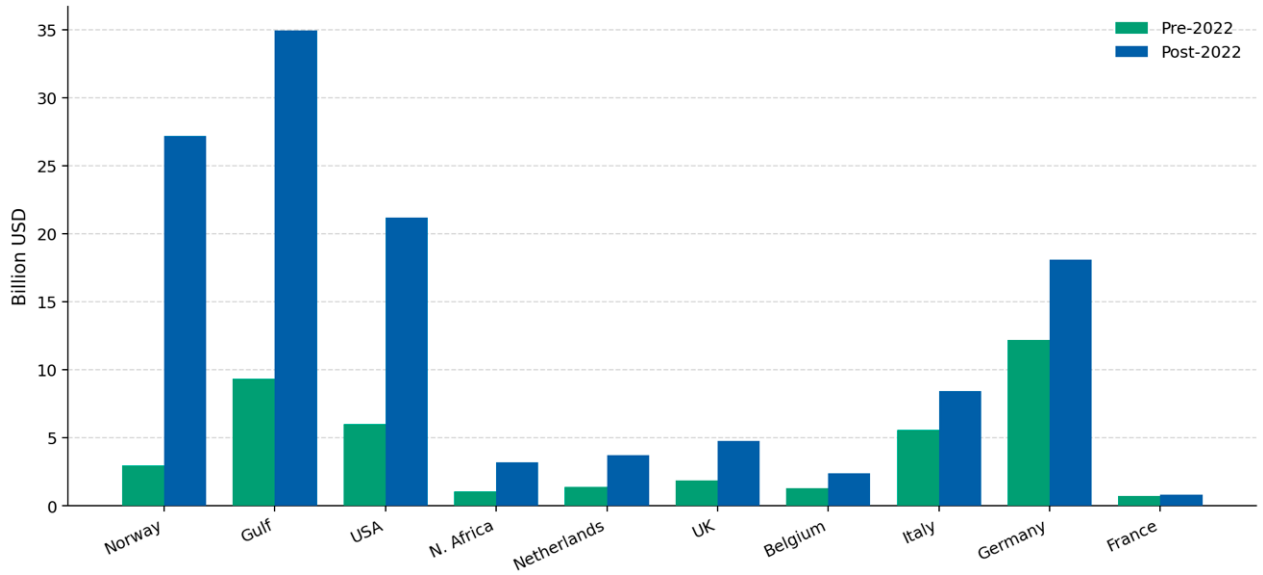
dominated by LNG exporters (the United States, the Gulf region, North Africa) and Norway as the principal provider of pipeline gas. The scale and asymmetry of these shifts are illustrated in Figure 1, which shows the pre- and post-2022 import volumes for each partner group.

Table 3. PPML gravity model estimates for export flows of energy products (HS27) – variant B (CEE as exporters)

Variable	Coefficient	Std. Error	Z-stat	p-value	95% CI (lower)	95% CI (upper)
Constant	16.847***	0.273	61.633	0.0	16.311	17.383
$\mathrm{Sanction}_{ijkt}$	−2.4128***	0.311	−7.77	0.0	−3.021	−1.804
$\mathrm{Brent}_t \cdot 1\{k \in \{2709, 2710\}\}$	0.0154***	0.003	5.136	0.0	0.01	0.021
$\mathrm{TTF}_t \cdot 1\{k = 2711\}$	0.0489***	0.013	3.793	0.0	0.024	0.074
$\mathrm{Coal}_t \cdot 1\{k = 2701\}$	0.0027*	0.002	1.758	0.079	−0.0	0.006
Country FE: Croatia	0.0873	0.235	0.371	0.71	−0.374	0.548
Country FE: Czechia	−0.8165***	0.235	−3.472	0.001	−1.277	−0.356
Country FE: Estonia	−0.7523***	0.25	−3.007	0.003	−1.243	−0.262
Country FE: Hungary	−0.3531	0.228	−1.552	0.121	−0.799	0.093
Country FE: Latvia	−1.2919***	0.262	−4.933	0.0	−1.805	−0.779
Country FE: Lithuania	0.1362	0.251	0.542	0.588	−0.357	0.629
Country FE: Poland	−0.412*	0.231	−1.783	0.075	−0.865	0.041
Country FE: Romania	0.1178	0.242	0.487	0.626	−0.356	0.591
Country FE: Slovakia	−0.0852	0.259	−0.329	0.742	−0.592	0.422
Country FE: Slovenia	−0.3252	0.268	−1.216	0.224	−0.849	0.199
Year FE: 2018	−0.0963	0.228	−0.422	0.673	−0.544	0.351
Year FE: 2019	−0.1374	0.226	−0.609	0.543	−0.58	0.305
Year FE: 2020	−0.3623	0.219	−1.657	0.097	−0.791	0.066
Year FE: 2021	−0.3368	0.228	−1.48	0.139	−0.783	0.109
Year FE: 2022	−0.2882	0.324	−0.89	0.374	−0.923	0.347
Year FE: 2023	−0.1417	0.239	−0.594	0.552	−0.609	0.326
Year FE: 2024	−0.1262	0.232	−0.544	0.586	−0.58	0.328

Notes: ***, **, and * indicate significant at the 1%, 5% and 10% levels, respectively. Bulgaria serves as the reference category for the country fixed effects; its coefficient is absorbed by the model intercept. Model fit: N = 10,823; df = 21; Log-Likelihood = -1.0295×10^{12}; Deviance = 2.0590×10^{12}; Pearson $\chi^2 = 9.96 \times 10^{12}$; Pseudo R^2 = 1.000.

Source: authors' calculations.



Note: Pre-2022 values represent cumulative imports for 2017–2021; post-2022 values cover 2022–2024. Gulf includes Saudi Arabia, the United Arab Emirates, Qatar, Kuwait, Oman and Bahrain. North Africa includes Algeria and Libya.

Figure 1. Changes in CEE energy imports by partner country/region before and after 2022 (HS27, billion USD)
Source: authors' calculations based on United Nations Comtrade 2025.

The PPML gravity model estimated for export flows (variant B, Table 3) indicates a very sharp decline in CEE exports to Russia and Belarus following the introduction of sanctions. The coefficient on the *Sanction* variable is negative and highly statistically significant (–2.4128, $p < 0.001$), corresponding to an export reduction of approximately 91% relative to the pre-sanction period. Energy price indices exert a positive and statistically significant effect on exports of crude oil (Brent) and natural gas (TTF), while the coal price index shows a weaker and only marginally significant effect.

The fixed effects at the country level reveal heterogeneous baseline levels of exports across CEE economies. Latvia, Czechia and Estonia display the lowest export levels, indicating that these countries were already sending relatively small volumes of energy products to Russia and Belarus before the sanctions. The model, therefore, reflects underlying structural differences rather than sanction-related declines in these specific cases.

The year fixed effects remain statistically insignificant, confirming that the sharp contraction in export flows is driven primarily by the sanction regime rather than by general trade-trend dynamics.

Table 4. GAP results: partner countries/regions to which CEE energy exports (HS27) changed the most after 2022 – model variant B

Partner country/region	Pre-2022 (USD billion)	Post-2022 (USD billion)	Δ Change (USD billion)	Δ Change (%)
Gulf	1.0457	0.3480	− 0.6977	− 66.72
France	0.6557	0.3264	− 0.3293	− 50.22
Norway	0.2490	0.1495	− 0.0995	− 39.94
Caspian	0.1591	0.1044	− 0.0547	− 34.36

Partner country/region	Pre-2022 (USD billion)	Post-2022 (USD billion)	Δ Change (USD billion)	Δ Change (%)
UK	1.0179	0.6804	− 0.3375	− 33.15
Belgium	0.9837	0.6820	− 0.3018	− 30.68
Germany	4.9596	3.4435	− 1.5161	− 30.57
North Africa	0.9065	0.6522	− 0.2543	− 28.05
Spain	0.3394	0.3271	− 0.0123	− 3.63
Other	170.1257	177.3252	7.1995	4.23

Notes: Caspian includes Kazakhstan and Azerbaijan; Gulf includes Saudi Arabia, the United Arab Emirates, Qatar, Kuwait, Oman and Bahrain; North Africa includes Algeria and Libya; Other covers all remaining countries not assigned to the specified groups.

Source: authors' calculations.

The selection of countries and regions in Table 4 follows the same logic as in the import-side GAP analysis: it includes the CEE countries' key trading partners and the major regional energy-market clusters that played an important role in HS27 trade prior to 2022. This set of partners allows for a direct comparison of changes on both the supply side (imports) and the demand side (exports), enabling an assessment of whether CEE countries were able to redirect their sales toward the same markets from which they sourced substitutes for Russian supplies.

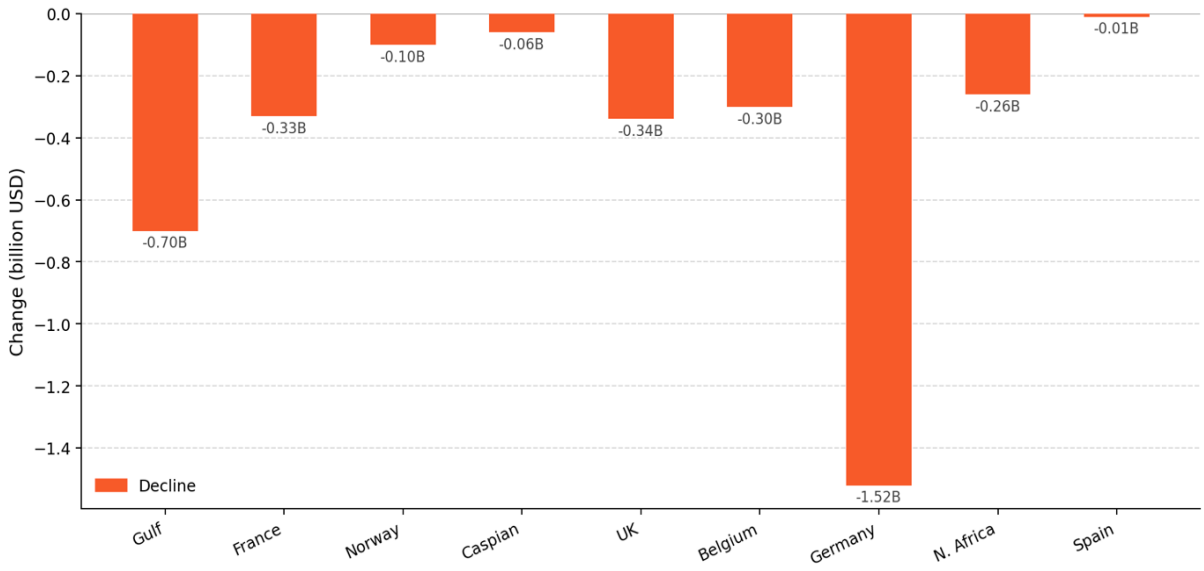
The GAP analysis of changes in CEE energy export destinations (HS27) shows that, following the loss of Russian and Belarusian markets, CEE countries were largely unable to significantly redirect their exports to other destinations. In contrast to import patterns, export adjustments are modest and, in many cases, clearly negative. The only group of destinations exhibiting an increase is the "Other" category representing markets outside the major trading partners where exports grew by just 4.23%. All other destinations recorded substantial declines in CEE export values, with the largest contractions observed for the Gulf region (–66.7%), France (–50.2%), Norway (–39.9%), the Caspian region (–34.4%), the UK (–33.2%), Belgium (–30.7%) and Germany (–30.6%). These results reflect the structural dependence of CEE refineries on low-cost Russian crude oil prior to 2022. Once access to Russian crude was restricted, production costs rose, and feedstock availability declined naturally leading to reduced export volumes of fuels and refined petroleum products to both European and global markets. Figure 2 illustrates the contrast between import-side and export-side adjustment: whereas imports expanded substantially across most partner groups, export flows declined almost universally, with only marginal gains recorded in the "Other" category.

Table 5. Re-export potential in CEE countries (in billion USD)

CEE country	Imports from non-CEE		Exports to CEE		Re-export Potential		Re-export Potential (Δ)	
	Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*	USD	%
Bulgaria	8.131	13.184	0.171	0.65	0.171	0.65	0.478	**279.0**
Croatia	4.566	12.336	0.414	1.339	0.414	1.339	0.925	**223.7**
Estonia	2.659	3.262	0.063	0.178	0.063	0.178	0.116	**184.7**

CEE country	Imports from non-CEE		Exports to CEE		Re-export Potential		Re-export Potential (Δ)	
	Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*	USD	%
Slovenia	4.74	9.285	0.438	1.139	0.438	1.139	0.701	**159.9**
Romania	10.888	18.374	0.602	1.51	0.602	1.51	0.908	**151.0**
Lithuania	10.439	18.534	1.417	3.07	1.417	3.07	1.653	**116.6**
Latvia	2.09	3.898	0.256	0.552	0.256	0.552	0.295	**115.3**
Czechia	15.42	27.687	0.889	1.418	0.889	1.418	0.529	**59.6**
Poland	33.756	58.917	0.83	1.256	0.83	1.256	0.426	**51.3**
Slovakia	11.04	17.429	1.332	1.655	1.332	1.655	0.323	**24.2**
Hungary	12.992	22.022	0.724	0.792	0.724	0.792	0.068	**9.3**

Source: authors' calculations.



Note: The "Other" category (pre-2022: USD 170.1 billion; post-2022: USD 177.3 billion) is excluded from the figure to preserve scale readability. Caspian includes Kazakhstan and Azerbaijan. Gulf includes Saudi Arabia, the United Arab Emirates, Qatar, Kuwait, Oman and Bahrain. North Africa includes Algeria and Libya. Pre-2022 values represent cumulative exports for 2017–2021; post-2022 values cover 2022–2024.

Figure 2. Changes in CEE energy export values by destination before and after 2022 (HS27, billion USD)
Source: authors' calculations based on United Nations Comtrade 2025.

The analysis of the RP indicator reveals substantial differences in how CEE countries adapted to the reshaping of the regional energy landscape after 2022 (Table 5). Applying a clustering approach based on RP dynamics distinguishes three groups of countries that responded differently to the disruption of traditional import routes from the Russian Federation.

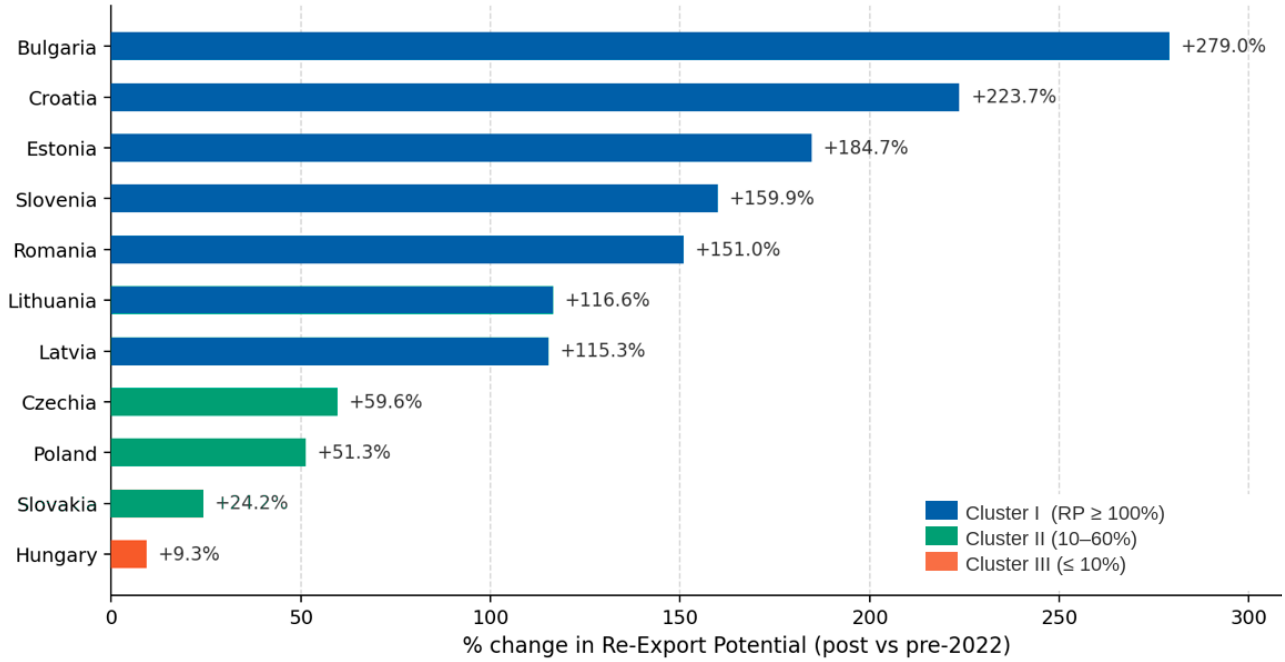
Cluster I (RP ≥ 100%): Bulgaria, Croatia, Romania, Slovenia, Lithuania, Estonia, and Latvia. Countries in this cluster recorded the largest increases in RP, exceeding 100% relative to the pre-2022 period. This reflects a simultaneous intensification of imports from outside the CEE region and an expansion

of intra-regional exports. Particularly strong increases are observed in Bulgaria (+279%) and Croatia (+224%), which corresponds to the rising importance of the Black Sea and Adriatic corridors as key diversification routes. Bulgaria's exceptionally high RP growth is primarily due to its hosting the largest refinery in the Balkans. After 2022, Bulgaria was the only CEE country allowed to continue importing Russian crude oil by sea under an EU exemption, which enabled it to maintain high production levels and increase exports of refined petroleum products to neighbouring CEE markets (Trusewicz 2025). As a result, Bulgaria effectively acted as a regional fuel hub reflected directly in its RP values. Croatia, in turn, is transforming into a regional energy hub for CEE. The floating LNG terminal on the island of Krk plays a pivotal role as an additional supply source and as a distribution point for gas flows to Hungary, Slovenia, and Romania. Combined with increasing investments in renewable energy, Croatia is strengthening its position as one of the region's main infrastructure nodes (Vienna Institute for International Economic Studies & Friedrich-Ebert-Stiftung 2023).

The strong dynamics observed in the Baltic states (Lithuania, Latvia, Estonia) are consistent with their complete phase-out of Russian imports and the intensive use of the LNG terminal in Klaipėda, Lithuania, which became the main entry point for non-Russian gas into the region after 2022. Infrastructure integration among the Baltic states also supports growing intra-regional exchange: Estonia has increased its flows to Lithuania, while Latvia sends substantial volumes of gas to Lithuania, part of which is subsequently directed to Poland. Collectively, the Baltic countries now function as a coherent and interconnected distribution corridor, which is directly reflected in their rising RP (International Energy Agency 2023; 2025b; Paszkowski 2025).

Cluster II (RP 10–60%): Czechia, Poland, and Slovakia. Countries in this cluster exhibit moderate yet statistically significant increases in RP. These economies have a large domestic demand and relatively high baseline values, which naturally limit relative growth. Czechia (+59.6%) and Poland (+51.3%) expanded imports from outside the CEE region, in line with European Commission (2024) data highlighting the growing role of LNG terminals and interconnections with Western European markets. Slovakia (+24.2%) maintains a stable transit role, consistent with reports on the sustained use of its transmission infrastructure (International Energy Agency 2024). The slower pace of adjustment in Slovakia and Hungary reflects not only domestic policy choices but also binding infrastructure constraints: both countries remain dependent on the Druzhba pipeline system, which lacks viable short-term alternatives and limits the speed at which supply diversification can be achieved.

Cluster III (RP ≤ 10%): Hungary. Hungary recorded the lowest RP dynamics (+9.3%), indicating a marginal role in energy redistribution. Despite increasing non-CEE imports, intra-regional exports did not rise, suggesting the predominance of domestic consumption. These results reflect Hungary's continued strong energy ties with Russia and its limited speed of diversification (Levi et al. 2025; Sabadus 2025). Figure 3 summarises the RP dynamics across all eleven CEE countries, highlighting the three-cluster structure and the markedly divergent adjustment trajectories within the region.



Note: Re-Export Potential (RP) is defined as the minimum of a country's HS27 imports from non-CEE partners and its HS27 exports to other CEE countries. Values reflect average annual figures for 2017–2021 (pre-2022) and 2022–2024 (post-2022). RP represents an upper-bound measure of potential intra-regional re-export flows, not an estimate of realised physical movements.

Figure 3. Re-export potential in CEE countries: percentage change between pre- and post-2022 periods (HS27)
Source: authors' calculations based on United Nations Comtrade 2025.

The RP results confirm a structural reshaping of the geographical distribution of energy flows within the CEE region. The most dynamic developments are observed in emerging Balkan, Adriatic and Baltic hubs, whereas the region's largest economies exhibit stable and moderate growth. Hungary continues to stand out as the country that most strongly deviates from regional diversification trends. The clustering outcomes fully reflect the direction of transformation described in institutional reports and the broader literature on Europe's energy security.

Policy Implications

The results of the study have a number of implications for energy policy in CEE. First, the almost complete stop of HS27 imports from Russia and Belarus shows that long-term supply relationships can be broken almost overnight. Diversification strategies should include pipeline supplies, LNG capacity, storage, and a wider range of crude and refined products. Second, the GAP results show that replacing imports has not been consistent across products and partners. Therefore, diversification policies should consider the technical limits of specific products in refineries and power systems.

Third, the limited redirection of CEE energy exports reflects structural weaknesses in refinery configuration and downstream market access. Policies for industry and energy should encourage investments that make it easier to use non-Russian feedstocks and boost regional demand that can absorb extra production. As the RP indicator represents an upper-bound measure of possible intra-regional flows

rather than an estimate of realised re-exports, policy conclusions regarding hub capacity should be interpreted accordingly.

Fourthly, the fact that few CEE hubs have a lot of potential for re-export shows how important cross-border infrastructure and coordinated EU-level planning for terminals, pipelines, and interconnections are for regional energy security. Finally, the structural vulnerabilities identified in this study extend beyond the current Russia–Ukraine context. Future geopolitical shocks whether affecting LNG supply routes, Gulf exporters, or key transit infrastructure could rapidly expose the remaining dependencies of CEE energy systems, reinforcing the case for continued diversification and regional coordination.

Conclusion

The analysis conducted in this study provides clear and consistent evidence addressing the research question and confirms both hypotheses formulated in the introduction.

First, the PPML model results support Hypothesis 1, demonstrating that EU sectoral sanctions and associated supply shocks after 2022 led to a profound reorientation of energy import structures in CEE countries. Following the introduction of EU sectoral sanctions, energy imports from Russia and Belarus declined by more than 99%, evidencing a profound disruption of prior trade linkages. GAP analysis further confirmed that this supply gap was filled by alternative suppliers primarily Norway, the Gulf states, the United States and North African exporters as well as by Western European energy hubs. Consequently, the import structure of the region underwent not only a rapid but also a structural and enduring transformation.

Second, the PPML estimates and GAP results also confirm Hypothesis 2, concerning changes in the export structure of energy products from CEE countries. Following the sanctions, exports to Russia and Belarus fell by more than 90%, while the region was largely unable to redirect its energy exports to alternative markets aside from a modest increase in the "Other" category. This indicates that, unlike imports, exports were not successfully diversified, reflecting higher production costs after the loss of Russian crude oil and the limited structural flexibility of CEE refineries.

A complementary analysis of the RP reveals that, after 2022, the region not only reconfigured its import sources but also underwent an internal reorganisation, forming new intra-regional energy distribution corridors. The strongest RP dynamics were recorded in the Balkan, Adriatic and Baltic states, which began to function as emerging regional hubs. These findings confirm that the transformation of energy trade in the CEE region is systemic in nature and is leading to the emergence of new economic functions within the region.

Taken together, recent policy developments, current import trends and the most up-to-date analytical assessments reinforce the empirical findings in this study. Europe's energy system has moved from short-term crisis management to a long-term structural transformation increasingly embedded in regulatory commitments and market practices. At the same time, persistent regional differences, especially in terms of continued infrastructural constraints affecting several CEE economies, remain crucial for understanding future re-export patterns, adjustment capacities, as well as individual member states' vulnerabilities.

In sum, this study provides coherent and robust evidence that the Russia–Ukraine war and the EU sanctions regime have become key drivers in the geographical reconfiguration of energy trade in CEE. This directly addresses the research question and confirms both hypotheses: the region successfully diversified its energy imports, while its capacity to restructure energy exports remained limited. The resulting transformation is structural in nature and likely to persist over the medium term, forming a new basis for further research into energy security and economic resilience in Central and Eastern Europe.

This research was funded by the research project *Potencjał Program*, No. 027/EEE/2025/POT, administered by the Kraków University of Economics.

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Comparative Economic Research. Central and Eastern Europe
Volume 29 Number 3, 2026
https://doi.org/10.18778/1508-2008.29.23

Beyond Physical Capital Accumulation: Does Human Capital Reduce the Reliance on Infrastructure in ASEAN-5?

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Abstract

This study investigates the nonlinear interaction between physical and human capital on economic growth across ASEAN-5 economies (Indonesia, Malaysia, the Philippines, Thailand, and Vietnam). Challenging the conventional capital-skill complementarity hypothesis, this research utilizes a macro-panel dataset (2000–2019) and employs the Fixed Effects estimator with Driscoll–Kraay standard errors to address cross-sectional dependence. The empirical results reveal a statistically significant negative interaction between mean-centered physical and human capital ($\beta_4 = -1.152$, $p < 0.001$). This indicates that as human capital levels rise above their sample mean, the marginal impact of physical capital accumulation diminishes – from 0.536 at the 10th percentile of HCI to 0.250 at the 90th percentile – providing evidence of structural transformation from investment-driven to efficiency-driven growth. The marginal effect remains positive throughout the observed range but declines monotonically. These findings imply that avoiding the Middle-Income Trap requires policymakers to pivot from "hard" infrastructure accumulation to "soft" infrastructure investments and synchronize industrial upgrading with workforce education.

Keywords: economic growth, human capital, physical infrastructure, structural transformation, Middle-Income Trap, ASEAN-5

JEL: H54, J24, O47, O53

Funding information: Universitas Sebelas Maret, Surakarta, Indonesia
The percentage share of the Authors in the preparation of the work is: M.B.S. – 33.33%, Y.P.P. – 33.33%, A.P. – 33.33%.
Conflicts of interests: None.
Ethical considerations: The Authors assure of no violations of publication ethics and take full responsibility for the content of the publication.
Received: 10.02.2026. Verified: 8.04.2026. Accepted: 2.07.2026

Introduction

The economic trajectory of the Association of Southeast Asian Nations (ASEAN) over the last two decades has featured a distinct phase of rapid development, positioning the region as a pivotal engine of the global economy. Catalyzed largely by rapid factor accumulation specifically through intensive physical infrastructure development and demographic expansion the ASEAN-5 economies (Indonesia, Malaysia, the Philippines, Thailand, and Vietnam) have successfully navigated the transition from low-income to middle-income status (Malarvizhi et al. 2019; Saida et al. 2021). Aggregate GDP growth in the region has consistently outpaced global averages, driven by substantial capital injections into transportation networks, energy systems, and manufacturing infrastructure (Wahyudi et al. 2023; Chaiboonsri et al. 2024; Ghosh and Paul 2025). However, as these economies mature, the viability of a growth model tethered exclusively to capital deepening faces critical scrutiny. The law of diminishing returns suggests that the relentless injection of physical capital, without a parallel leap in total factor productivity, leads to inevitable stagnation a phenomenon widely characterized as the "Middle-Income Trap" (Affandi, Anugrah, and Bary 2019; Goh 2025).

Standard neoclassical growth theories, rooted in the Solow–Swan tradition, typically treat physical and human capital as distinct inputs that additively contribute to output. A dominant view in the development literature is the "capital-skill complementarity" hypothesis, which posits a symbiotic relationship: educated labor enhances the productivity of machinery, implying that simultaneous investment in both vectors should trigger increasing returns (Tsaurai and Ndou 2019; Chang, Fang, and Hamori 2020). However, this assumption of linearity risks oversimplifying the structural dynamics of developing nations. As countries pivot from agrarian roots through industrialization toward knowledge-based complexity, the hierarchy of input needs shifts. The relative supremacy of "hard infrastructure" (physical capital) versus "soft infrastructure" (human capital) is not constant; it evolves (Budsayaplakorn and Sompornserm 2021; Tasane and Srun 2023).

Despite a proliferation of literature on Asian growth, empirical clarity on the specific interaction between these two forms of capital remains elusive, particularly within the ASEAN-5 context. Previous studies reveal mixed signals. For instance, Sirisunhirun and Vajrapatkul (2023) found that while Thailand and Malaysia have nearly maximized technical efficiency in human capital, they simultaneously confront declining returns to scale in physical accumulation. Similarly, Amar, Ariusnu, and Satrianto (2025) found that while education and infrastructure both matter, their impacts are volatile and contingent on institutional nuances (Jama, Mohd Daud, and Nayan 2024; Patiu and Nayve 2025).

This study bridges this gap by investigating the nonlinear interaction between physical and human capital across the ASEAN-5 region from 2000 to 2019. We hypothesize that the relationship is conditional: as an economy's human capital reservoir deepens, the marginal utility of physical capital accumulation alters. Methodologically, we deploy the Fixed Effects estimator with Driscoll–Kraay (1998) standard errors, confirmed by the Pesaran (2004) CD test (CD = 3.723, $p = 0.0002$), which detects significant cross-sectional dependence arising from ASEAN's economic integration (Abdul Bahri and Wye 2024; Suwanhirunkul and Suwanhirunkul 2025).

The empirical results reveal that the mean-centered interaction term is statistically significant and negative ($\beta_4 = -1.152$, $p < 0.001$). The marginal effect of physical capital on growth declines monotonically

from 0.536 at low human capital levels (10th percentile, where the Human Capital Index (HCI) = 2.24) to 0.250 at high human capital levels (90th percentile, HCI = 2.87). The effect remains positive throughout the observed range, indicating that physical capital is not counterproductive, but its growth contribution diminishes substantially as human capital deepens. This finding is robust across 11 of 12 sensitivity specifications. The remainder of this paper is organized as follows: Section 2 reviews the theoretical framework; Section 3 outlines data and methodology; Sections 4 and 5 present results and discussion; Section 6 concludes.

Literature Review and Hypotheses Development

Theoretical Framework: Augmented Solow and Structural Shifts

This study is grounded in the Augmented Solow Model (Mankiw, Romer, and Weil 1992), which extends the classical neoclassical framework by treating human capital as a distinct factor of production alongside physical capital. While standard growth accounting assumes that physical capital (K) and human capital (H) contribute to output additively with constant elasticity, modern endogenous growth theories challenge this linearity. As economies evolve from agrarian bases to industrial and knowledge-based structures, the relationship between production factors is dynamic rather than static (Chang, Fang, and Hamori 2020; Thach 2025). This study explicitly investigates the interaction term ($\ln K^c \times \ln H^c$) to test whether the marginal productivity of physical infrastructure remains constant as human capital deepens.

An important strand of theory directly relevant to this inquiry concerns formal models of structural transformation. The classic dual-sector framework proposed by Lewis (1954) provides a foundational lens: in early development stages, physical capital accumulation in the modern sector is the binding constraint. As economies industrialize and the labor surplus is exhausted, this mechanism loses potency. More recent multi-sector growth frameworks have formalized this insight. Models in the tradition of Kongsamut, Rebelo, and Xie (2001) and Ngai and Pissarides (2007) demonstrate that structural change the reallocation of resources across sectors with heterogeneous productivity levels is an intrinsic feature of the growth process. In these frameworks, the relative importance of physical capital versus human-capital-intensive activities shifts endogenously as income rises, providing explicit theoretical grounding for our interaction specification.

The Debate: Complementarity vs. Substitution

The empirical literature offers two competing hypotheses. For clarity, we organize the discussion by first presenting the theoretical mechanisms advanced in each tradition, followed by the empirical evidence that tests these mechanisms.

The Capital-Skill Complementarity Hypothesis

Griliches (1969) formalized the idea that sophisticated machinery requires educated labor for efficient operation. Lucas (1988) extended this logic: human capital accumulation generates positive externalities that amplify the productivity of all other factors, including physical infrastructure, creating a supermodular production structure.

Empirical support for complementarity has been documented in developing-country contexts where physical infrastructure remains a binding constraint. Zergawu, Walle, and Giménez-Gómez (2020) and Wang et al. (2021) found that infrastructure quality amplifies growth when paired with strong human capabilities. Tsaurai and Ndou (2019), studying transitional economies, found positive synergies between infrastructure investment and human capital development, a pattern mirrored in Ramlan and Ahmed (2009), who documented complementary gains from ICT infrastructure and human capital management in Malaysia.

The Structural Transformation Hypothesis

As an economy matures, the primary driver of value shifts from factor accumulation to efficiency and innovation (Maneejuk and Yamaka 2021). This is formalized in multi-sector models where, at later stages, as skilled workforces expand, comparative advantage shifts toward knowledge-intensive services relying on intangible assets rather than physical plant. Continued heavy investment in physical capital yields declining marginal returns once human capital reaches a threshold, implying that economies must shift from "building more" to "using better" (Budsayaplakorn and Sompornserm 2021; Thach 2025).

Empirical evidence for structural transformation has grown, particularly in middle-income Asian contexts. Sirisunhirun and Vajrapatkul (2023) found that Thailand and Malaysia confront declining returns to scale in physical accumulation. Meanwhile, Maneejuk and Yamaka (2021) found that in more advanced ASEAN-5 members, human capital has become the dominant growth driver, with the marginal contribution of physical infrastructure weakening over time. ASEAN's diverse development landscape makes it an ideal testing ground for discriminating between these hypotheses.

Research Hypotheses

H1: Physical capital and human capital independently exert positive effects on economic growth in ASEAN-5 economies.

H2: The interaction between physical capital and human capital is negative, indicating that as human capital deepens, the marginal contribution of physical capital to growth diminishes, consistent with structural transformation.

Data and Methodology

Data and Variables

This study employs a balanced panel dataset comprising the ASEAN-5 economies over the period 2000–2019 (N = 5, T = 20, 100 observations). The dependent variable is the natural logarithm of real GDP per capita (constant 2015 USD). The key independent variables are:

- Physical Capital (K): Natural logarithm of gross fixed capital formation as a percentage of GDP (ln GFCF). Global sample mean: 25.79% of GDP (World Bank WDI).
- Labor (L): Natural logarithm of total labor force (in persons), controlling for demographic scale differences across ASEAN-5 economies (World Bank WDI; Mankiw, Romer, and Weil 1992).
- Human Capital (H): Natural logarithm of the Human Capital Index (HCI) from Penn World Table 10.01 (global sample mean: 2.525). The HCI aggregates years of schooling and returns to education into a composite measure of workforce quality.

Following standard econometric practice for interaction models (Aiken and West 1991; Brambor, Clark, and Golder 2006), we construct the interaction term after globally mean-centering both lnK and lnH to reduce multicollinearity – a critical concern with N = 5:

$$\ln K_{it}^{c} = \ln K_{it} - \overline{\ln K}\ \left(= 3.250\right);\ \ \ln H_{it}^{c} = \ln H_{it} - \overline{\ln H}\ \left(= 0.926\right);$$
$$\mathrm{INT}_{it} = \ln K_{it}^{c} \times \ln H_{it}^{c}.$$

Control variables include Trade Openness (TRADE; exports + imports as % GDP, following Sachs and Warner 1995), Government Consumption (GOV; % GDP, following Barro 1991), and Inflation (INF; GDP deflator, following Barro 1996). All data are sourced from the World Bank WDI and PWT 10.01. Descriptive statistics and the correlation matrix are presented in Tables 1 and 2, respectively.

Table 1. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Ln GDP per capita	100	8.1502	0.5736	7.1002	9.2968
Ln Physical Capital (K)	100	3.2502	0.2130	2.7527	3.6780
Ln Labor (L)	100	17.5020	0.7290	16.0131	18.7386
Ln Human Capital (H)	100	0.9263	0.0978	0.6791	1.1245
Trade Openness (TRADE)	100	110.583	46.610	37.421	220.407
Gov. Consumption (GOV)	100	10.910	2.934	5.465	17.121
Inflation (INF)	100	5.434	6.191	−5.992	42.303

Notes: N = 5 countries, T = 20 years (2000–2019).

Source: World Bank WDI and Penn World Table (PWT) 10.01.

Table 2. Correlation matrix

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) Ln GDP per capita	1.000	− 0.193	− 0.616	0.764	0.498	0.743	− 0.395
(2) Ln K	− 0.193	1.000	0.422	− 0.341	0.040	− 0.331	0.299
(3) Ln L	− 0.616	0.422	1.000	− 0.594	− 0.768	− 0.409	0.272
(4) Ln H	0.764	− 0.341	− 0.594	1.000	0.388	0.597	− 0.363
(5) TRADE	0.498	0.040	− 0.768	0.388	1.000	0.323	− 0.085
(6) GOV	0.743	− 0.331	− 0.409	0.597	0.323	1.000	− 0.444
(7) INF	− 0.395	0.299	0.272	− 0.363	− 0.085	− 0.444	1.000

Notes: Yellow-shaded cells indicate |r| > 0.70. High-correlation pairs: (1)&(4) r = 0.764; (1)&(6) r = 0.743; (3)&(5) r = −0.768. Global mean-centering of lnK and lnH prior to interaction term construction substantially mitigates multicollinearity between regressors and their product term. Variance Inflation Factors (VIF) are reported in Appendix Table A2; all values fall below 10 (mean VIF = 3.44), confirming the absence of severe multicollinearity.

Source: author processed, 2026

Econometric Strategy

This study adopts a Fixed Effects (FE) model with Driscoll–Kraay standard errors. The baseline specification is:

$$\ln(\mathrm{GDPpc})_{it} = \alpha + \beta_1 \ln K^c_{it} + \beta_2 \ln L_{it} + \beta_3 \ln H^c_{it} + \beta_4 (\ln K^c \times \ln H^c)_{it} + \beta_5 \mathrm{TRADE}_{it} + \beta_6 \mathrm{GOV}_{it} + \beta_7 \mathrm{INF}_{it} + \mu_i + \varepsilon_{it}, \ \ldots, \quad (1)$$

where μ_i represents country fixed effects, imposed along the cross-sectional (country) dimension, not time, to preserve degrees of freedom (N = 5, T = 20). The Driscoll–Kraay (1998) estimator is selected for its non-parametric robustness under general spatial and temporal dependence, superior to Panel-Corrected Standard Errors (PCSE) (Beck and Katz 1995), which imposes parametric assumptions difficult to verify with N = 5, and to the Common Correlated Effects (CCE) estimator (Pesaran 2006), which may be unreliable in small-N settings. Endogeneity from time-varying confounders is partially mitigated by country fixed effects. However, a full Generalized Method of Moments (GMM) approach is infeasible as the instrument count would exceed N = 5 (Arellano and Bond 1991; Blundell and Bond 1998; Roodman 2009). Panel diagnostics in Table 3 confirm CSD (Pesaran CD = 3.723, p = 0.0002) and FE preference (Hausman χ^2 = 192.196, p = 0.000).

Table 3. Panel diagnostic tests

Diagnostic Test	Null Hypothesis (H_0)	Statistic	*p*-value	Conclusion
Cross-Sectional Dependence				
Pesaran (2004) CD Test	Cross-sectional independence	3.723	0.0002***	CSD detected → Driscoll–Kraay SE
Fixed Effects vs. Random Effects				
Hausman (1978) Test	RE estimates are consistent	χ^2 = 192.196	0.0000***	Reject RE → FE preferred
Panel Unit Root				
Panel ADF – lnGDP pc	Series is non-stationary	− 0.071	–	Non-stationary; FE within-transformation applied
Panel ADF – lnK (GFCF)	Series is non-stationary	− 1.656	–	Non-stationary; within R^2 > 0.91 supports long-run relationship
Panel ADF – lnH (HCI)	Series is non-stationary	− 1.491	–	Non-stationary; FE within-transformation addresses unit root

Notes: *** denotes significance at the 0.1% level. Panel ADF statistics are panel mean ADF values (demeaned series, maxlag = 1).
CD = cross-sectional dependence; SE = standard errors; RE = random effects; FE = fixed effects; ADF = Augmented Dickey–Fuller; Ln = natural logarithm; GDP pc = GDP per capita; K = physical capital; GFCF = gross fixed capital formation; H = human capital; HCI = Human Capital Index.
Dashes (–) in the p-value column indicate that the panel ADF test reports a test statistic without a conventional p-value in this specification.

Source: author processed, 2026

Interpretation of the Interaction Term

With globally mean-centered variables, β_1 represents the marginal effect of lnK at the sample mean of lnH, and β_4 captures how this marginal return changes as $\ln H^c$ deviates from its mean. The full marginal effect is:

$$\frac{\partial \ln (\mathrm{GDPpc})_{it}}{\partial \ln K_{it}^c} = \beta_1 + \beta_4 \times \ln H_{it}^c, \ \ldots \tag{2}$$

A negative and significant β_4 indicates diminishing marginal returns to physical capital as human capital rises, supporting the structural transformation hypothesis. Marginal effects are computed and visualized with 95% confidence intervals (delta method) across the empirical distribution of $\ln H^c$ in Figure 1.

Empirical Results

Baseline Results

Table 4 presents the regression results for three models: Model 1 (baseline, no interaction), Model 2 (interaction model), and Model 3 (full controls).

Table 4. The effect of physical and human capital on economic growth (FE with Driscoll–Kraay standard errors)

	(1) Baseline	(2) Interaction	(3) Full Controls
Dependent Variable: Ln GDP per capita			
Ln Physical Capital ($\ln K^c$)	0.4233***	0.3977***	0.2360***
	(0.0193)	(0.0178)	(0.0109)
Ln Labor (lnL)	0.6290***	0.5593***	1.0682***
	(0.0192)	(0.0190)	(0.0196)
Ln Human Capital ($\ln H^c$)	1.8676***	2.0798***	1.1483***
	(0.0226)	(0.0326)	(0.0310)
Interaction ($\ln K^c \times \ln H^c$)	–	− 1.1522***	− 1.9335***
		(0.0860)	(0.1084)
Trade Openness (TRADE)	–	–	0.0029***
			(0.0001)
Gov. Consumption (GOV)	–	–	0.0234***
			(0.0007)
Inflation (INF)	–	–	− 0.0029***
			(0.0002)
Robust SE (Driscoll–Kraay)	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Time FE	No	No	No
Observations	100	100	100
R^2 (within)	0.9131	0.9177	0.9447
Adj. R^2	0.9065	0.9105	0.9377
F-statistic	322.422	253.811	214.594

Notes: Driscoll–Kraay SE in parentheses (DK bandwidth = 2). Country FE included; time FE excluded to preserve degrees of freedom. $\ln K^c$ and $\ln H^c$ are globally mean-centered ($\bar{\ln K} = 3.250$, $\bar{\ln H} = 0.926$). *** denotes significance at the 0.1% level. Dashes (–) indicate that the variable is not included.

Source: author processed, 2026

The results in Model 1 confirm that physical capital ($\beta_1 = 0.423$, $p < 0.001$), labor ($\beta_2 = 0.629$, $p < 0.001$), and human capital ($\beta_3 = 1.868$, $p < 0.001$) each independently exert positive and statistically significant effects on GDP per capita, supporting Hypothesis 1. Economically, a 1% increase in physical capital at mean human capital levels is associated with a 0.423% increase in GDP per capita, while a 1% increase in human capital at mean physical capital levels is associated with a 1.868% increase. The substantially larger coefficient for human capital suggests that workforce quality is the dominant growth factor in the ASEAN-5 context, consistent with the augmented Solow framework (Mankiw, Romer, and Weil 1992).

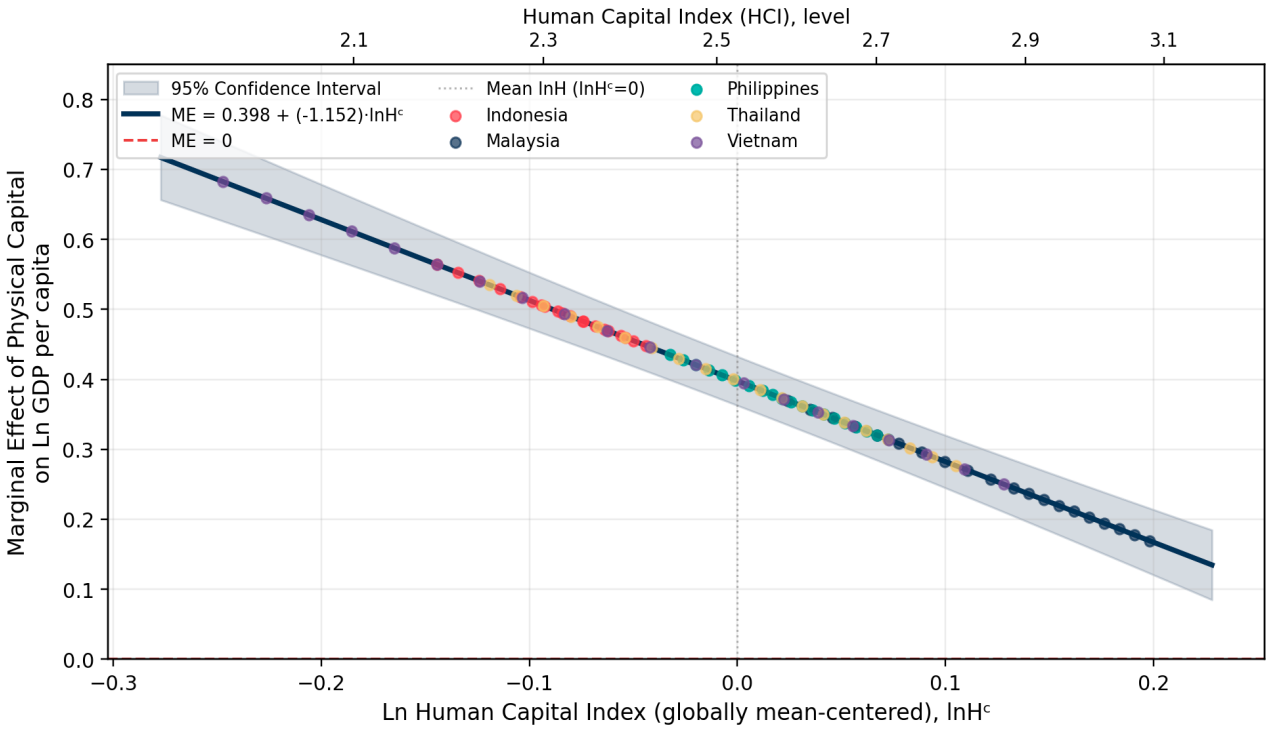
In Model 2, introducing the mean-centered interaction term yields a negative and highly significant coefficient ($\beta_4 = -1.152$, $p < 0.001$), confirming Hypothesis 2. With mean-centered variables, the main effect $\beta_1 = 0.398$ is interpreted as the marginal effect of lnK evaluated at the sample mean of lnH. Economically, for each one-unit increase in $\ln H^c$ (a 1% deviation of HCI above its mean), the marginal return to physical capital declines by 1.152 percentage points. This is not merely a statistical artifact: it represents a meaningful structural shift whereby economies with deeper human capital stocks such as Malaysia and Thailand, with HCI near the upper end of the ASEAN-5 distribution gain proportionally less from additional physical infrastructure compared to economies at earlier human capital development stages. The within-R^2 rises from 0.913 (Model 1) to 0.918 (Model 2), confirming the interaction captures economically relevant variation.

In Model 3, after controlling for trade openness, government consumption, and inflation, the interaction term becomes even larger in magnitude and remains highly significant ($\beta_4 = -1.934$, $p < 0.001$), providing strong reassurance that the finding is not driven by omitted macroeconomic factors. The control variables behave as expected: trade openness positively influences growth ($\beta_5 = 0.003$, $p < 0.001$), consistent with Suwanhirunkul and Suwanhirunkul (2025); government consumption has a positive effect ($\beta_6 = 0.023$, $p < 0.001$); and inflation exerts a negative impact ($\beta_7 = -0.003$, $p < 0.001$), consistent with macroeconomic instability hindering growth (Barro 1996). The within-R^2 of 0.945 indicates that the full specification explains an economically large share of within-country variation in GDP per capita.

Marginal Effects Analysis

To illustrate the economic significance of the interaction, Figure 1 plots the marginal effect of physical capital on growth (Equation 2) across the observed distribution of $\ln H^c$. Using $\beta_1 = 0.398$ and $\beta_4 = -1.152$ from Model 2, the marginal effect at key percentiles of the HCI distribution is as follows: at the 10th percentile (HCI = 2.240, representative of early-period Vietnam and Indonesia), the marginal effect equals 0.536; at the 50th percentile (HCI = 2.546, sample mean), it equals 0.388; and at the 90th percentile (HCI = 2.871, representative of Malaysia and Thailand at the development frontier), it equals 0.250. All marginal effects are statistically significant at $p < 0.001$ throughout the observed range.

Critically, the marginal effect remains positive across all observed HCI values – the zero crossing occurs at HCI $\approx$ 3.566, which lies above the empirical maximum in the sample (HCI = 3.081). This corrects an earlier narrative: physical capital does not become counterproductive within the ASEAN-5 context. Rather, its growth contribution diminishes substantially but remains economically meaningful. The pattern fully supports the structural transformation hypothesis: economies at earlier development stages benefit more from "building roads and factories," while economies with deeper human capital gain more from "upgrading skills and technology."



Note: The downward-sloping line shows the marginal effect of lnK^c on ln GDP per capita ($\beta_1 + \beta_4 \times \ln H^c$) from Model 2. Shaded band = 95% confidence interval (delta method). Colored dots = country-year observations. Red dashed line = ME = 0 (not reached within the empirical range). Upper axis = HCI levels.

Figure 1. Marginal effect of physical capital conditional on human capital levels in ASEAN-5 (2000–2019)
Source: authors' calculations based on WDI (World Bank) and Penn World Table 10.01.

Robustness Checks

To ensure the credibility of our findings, we conducted 12 sensitivity analyses, presented in Table 5, which is consistent with methodological recommendations for small-N panel robustness (Hoechle 2007; Roodman 2009).

Table 5. Robustness checks: interaction term (β_4) across alternative specifications

Specification	β_4 (INT)	(SE)	p-value	Sig.
(1) Baseline: Model 2 (DK SE)	− 1.1522	(0.0860)	0.0002	***
(2) Alt. H: Years of Schooling (Barro–Lee proxy)	1.8607	(0.0631)	0.0000	***†
(3) Alt. K: GFCF in levels (not logged, centered)	− 0.0293	(0.0030)	0.0006	***
(4) Alternative estimator: PCSE	− 1.1522	(0.4299)	0.0552	.
(5) Sub-period: 2000–2009	− 0.4005	(0.0644)	0.0034	**
(6) Sub-period: 2010–2019	− 1.3442	(0.2287)	0.0042	**
(7) Winsorized (1st–99th pct.)	− 1.2439	(0.0889)	0.0002	***
(8) Leave-one-out: drop Indonesia	− 0.5883	(0.0693)	0.0034	**

Specification	β_4 (INT)	(SE)	p-value	Sig.
(9) Leave-one-out: drop Malaysia	− 1.4497	(0.0756)	0.0003	***
(10) Leave-one-out: drop Philippines	− 1.2572	(0.1053)	0.0013	**
(11) Leave-one-out: drop Thailand	− 0.5707	(0.1544)	0.0344	*
(12) Leave-one-out: drop Vietnam	− 3.7880	(0.1842)	0.0003	***

Notes: All specifications use country FE and Driscoll–Kraay SE unless stated. † Specification (2) uses secondary school enrollment rates as a proxy for Barro–Lee years of schooling; the positive sign reflects the qualitatively different information captured by enrollment rates vs. the PWT HCI composite (see text). Purple shading = leave-one-out analyses. Blue shading = sub-period analyses. Yellow shading = positive β_4. ***, **, * denote significance at 0.1%, 1%, 5%.

Source: authors' calculations based on WDI (World Bank) and Penn World Table 10.01.

The robustness results are strongly supportive of H2. Of the 12 specifications, 11 show a negative interaction coefficient ($\beta_4 < 0$), significant at conventional levels. The single exception is specification (2), where the positive sign is expected because secondary school enrollment rates capture investment flows rather than the stock of accumulated workforce quality measured by the PWT HCI. This distinction is standard in the human capital literature (Mankiw, Romer, and Weil 1992).

The leave-one-out analysis (specifications 8–12) addresses the standard concern in small-N panel estimation that with $N = 5$, results may be driven by a single influential observation (Roodman 2009). The interaction coefficient is negative and statistically significant after dropping each of the five countries in turn, ranging from −0.571 (drop Thailand, $p = 0.034$) to −3.788 (drop Vietnam, $p = 0.000$). The larger magnitude when Vietnam is excluded reflects that Vietnam's combination of low HCI and high GFCF growth during rapid industrialization modestly attenuates the estimated coefficient in the full sample. Nonetheless, the negative sign is consistent across all five permutations, confirming that the structural transformation pattern is a genuine regional feature of ASEAN-5, not an artifact of any single economy.

Discussion

Theoretical Implications

The empirical evidence decisively supports the structural transformation hypothesis over the capital-skill complementarity view in the ASEAN-5 context. The negative interaction (β_4 ranging from −1.152 to −1.934 across specifications) suggests that the region is transitioning from an investment-driven growth model to an efficiency-driven model. This is consistent with the dual-sector framework of Lewis (1954) and the multi-sector models of Kongsamut, Rebelo, and Xie (2001) and Ngai and Pissarides (2007), which predict that as economies approach structural transformation, the binding growth constraint shifts from physical capital toward human capital and total factor productivity.

This finding resonates with Krugman's (1994) critique of Asian growth as "input-driven" rather than "productivity-driven." Our results indicate that ASEAN-5 is at a critical juncture. Importantly,

the positive marginal effects throughout the observed range indicate that physical capital is not counterproductive economies should not abandon infrastructure investment. Rather, the findings suggest that continued growth at the frontier increasingly requires complementary investments in human capital, innovation, and institutional quality to realize the full return on physical infrastructure.

Policy Recommendations

The findings of this study suggest the following strategic shifts:

1. Rebalance Investment Priorities: The marginal return differential (0.536 at low HCI vs. 0.250 at high HCI) suggests that incremental gains are now higher in human capital development, particularly for Malaysia and Thailand, which sit at the upper end of the HCI distribution.
2. Synchronize Industrial Policy with Education: Industrial upgrading strategies must be aligned with workforce skills. Attracting high-tech manufacturing requires not just tax incentives and industrial parks but also technical and vocational education systems.
3. Focus on Quality, Not Quantity: Rather than expanding the sheer volume of infrastructure, focus on improving utilization efficiency. The leave-one-out analysis confirms the over-investment concern is a regional, not country-specific, phenomenon.
4. Strengthen Innovation Systems: Invest in research universities, innovation hubs, and technology transfer mechanisms to complement physical infrastructure at high human capital levels.
5. Regional Cooperation: ASEAN should leverage regional integration to share knowledge, harmonize education standards, and facilitate cross-border labor mobility.

Limitations and Future Research

This study has several limitations. First, the sample is restricted to ASEAN-5; future research should include CLM countries or utilize firm-level microdata. Second, the macro-level HCI does not distinguish vocational from tertiary education; future studies should disaggregate human capital to identify which skills drive structural transformation most effectively. Third, longer panels would enable more rigorous endogeneity correction through IV or difference-GMM. Fourth, the log-level specification treats the relationship as a long-run level equation; future work could employ panel error-correction models that jointly identify short-run and long-run effects.

Conclusion

This study provides robust empirical evidence that the relationship between physical and human capital in ASEAN-5 is characterized by diminishing returns rather than complementarity. As human capital deepens above the sample mean, the marginal contribution of physical infrastructure to economic growth declines monotonically from 0.536 at low human capital levels (HCI = 2.24) to 0.250 at high

human capital levels (HCI = 2.87) signaling a structural transformation from investment-driven to efficiency-driven growth. The effect remains positive throughout the observed range, clarifying that physical capital is not counterproductive but is decreasingly sufficient as the primary growth engine. This finding holds across 11 of 12 robustness specifications, including sub-period analyses, alternative estimators, winsorized samples, and all five leave-one-out permutations. To escape the Middle-Income Trap, ASEAN economies must pivot from relentless infrastructure expansion to strategic investments in human capital, innovation, and institutional quality. The era of "build more" is giving way to the imperative of "use better."

Funding: This research was funded by Universitas Sebelas Maret through the Penguatan Kapasitas Grup Riset (PKGR-UNS) B scheme under contract number 462/UN27.22/PT.01.03/2026.

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Comparative Economic Research. Central and Eastern Europe
Volume 29 Number 3, 2026
https://doi.org/10.18778/1508-2008.29.24

Remittance-scapes: How Diaspora Financial Flows Influence Rural Capital Formation and Development

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Abstract

Diaspora remittances constitute a critical source of household income and foreign exchange in Zimbabwe, yet their contribution to gross capital formation in rural areas remains ambiguous. This study systematically reviews 62 empirical and policy studies using a PRISMA-guided approach to examine how remittances interact with rural investment environments. The findings reveal that remittances primarily finance consumption, education, healthcare, and housing, with limited allocation to productive assets or rural enterprises. Housing investment, while significant, provides minimal economic spillovers in the absence of complementary infrastructure and market linkages. Macro-level constraints, including inflation, currency volatility, and policy uncertainty, alongside institutional weaknesses such as insecure land tenure and underdeveloped rural financial systems, restrict the transformation of remittances into sustainable capital accumulation. Spatial analysis further indicates an urban bias in remittance-financed investments, exacerbating rural–urban inequalities. The study applies the remittance-scapes framework to conceptualise the socio-economic and spatial pathways through which remittances flow, highlighting structural impediments to productive investment. Policy implications emphasise macroeconomic stability, rural financial inclusion, land tenure reform, and diaspora-targeted investment instruments to enhance remittance-driven rural development. The study also identifies gaps for future research, including longitudinal analyses, collective investment mechanisms, and the measurement of remittance impacts on specific components of rural gross capital formation.

Keywords: diaspora remittances, gross capital formation, rural investment, rural development, remittance-scapes, financial flows

JEL: D14, F24, O12, O16, R58

Funding information: Research Associate: College of Economic & Management Sciences, UNISA, Pretoria, South Africa;, Lecturer: Department of Banking & Finance, BUSE, Bindura, Zimbabwe
Conflicts of interests: None.
Ethical considerations: The Author assures of no violations of publication ethics and takes full responsibility for the content of the publication.
Received: 27.02.2026. Verified: 9.04.2026. Accepted: 7.07.2026

Introduction

Diaspora remittances have become a cornerstone of Zimbabwe's socio-economic survival strategy amid prolonged economic instability, structural transformation challenges, and constrained access to international capital markets. Over the past two decades, Zimbabwe has experienced sustained outward migration, resulting in a large and economically active diaspora primarily located in South Africa, the United Kingdom, Australia, and other parts of the global North. The financial transfers from this diaspora have emerged as one of the country's most stable and countercyclical sources of foreign inflows, often exceeding foreign direct investment and official development assistance in certain years (Newland and Patrick 2004; Brinkerhoff 2008; Debass and Ardovino 2009; Terrazas 2010; Gelb et al. 2021). Despite their macroeconomic significance, the contribution of diaspora remittances to gross capital formation, particularly in rural areas, remains insufficiently understood and under-examined (Duresa 2025; Jonasi et al. 2025).

Rural Zimbabwe is characterised by persistent underinvestment in productive infrastructure, limited access to formal finance, and declining agricultural productivity (Kuipa 2019; Chamba and Tarirai 2024; Chinamatira and Śmiglak-Krajewska 2025). While remittances play a critical role in sustaining rural household consumption, that is, financing food security, education, healthcare, and housing, their ability to stimulate long-term capital accumulation and productive investment remains ambiguous. The concept of remittance-scapes provides a useful analytical framework for examining how remittance flows are spatially embedded within rural Zimbabwean communities and how social norms, institutional arrangements, and economic constraints shape their utilisation (Cirolia, Hall, and Nyamnjoh 2022; Guermond 2022).

Gross capital formation is a fundamental driver of rural development, encompassing investments in farm equipment, irrigation systems, agro-processing facilities, rural housing, transport infrastructure, and small-scale enterprises (Mpogole, Dimoso, and Mayaya 2020; Banerjee 2022; Jadhav 2025). However, despite substantial remittance inflows at the household level, rural Zimbabwe continues to exhibit low levels of fixed capital accumulation. This apparent disconnect raises a critical development paradox: why do remittances, which augment household incomes and relax liquidity constraints, fail to translate into sustained rural capital formation?

Several structural and institutional factors underpin this paradox. Zimbabwe's volatile macroeconomic environment, which is characterised by chronic inflation, currency instability, and policy uncertainty, has significantly eroded incentives for long-term investment (Kramarenko et al. 2010; Makoto 2020; Mbambi 2024). In rural areas, weak property rights, limited land tenure security under the fast-track land reform programme, and the absence of well-functioning rural credit markets further constrain the productive deployment of remittances (Cousins and Scoones 2010). As a result, remittances are often channelled toward immediate consumption needs, housing construction with limited productive spillovers, or informal savings mechanisms rather than capital-enhancing investments.

Furthermore, the spatial and social dimensions of remittance use in Zimbabwe reveal deep rural-urban and centre-periphery disparities (Van Zijll de Jong 1995; Magidimisha and Chipungu 2019; Mulungu 2021). Remittance-funded investments tend to gravitate toward urban real estate,

retail trade, and services, where returns are perceived to be more secure, leaving rural economies marginalised. In this context, remittance-scapes are shaped not only by household preferences but also by the broader investment climate, infrastructure deficits, and the absence of coordinated policies linking diaspora finance to rural development strategies (Guermond 2022; Warnecke-Berger 2022).

This study explores the impact of diaspora remittances on gross capital formation in rural Zimbabwe through the lens of remittance-scapes. By analysing how remittance flows interact with local investment environments, institutional frameworks, and livelihood systems, the paper seeks to move beyond simplistic assessments of remittances as either productive or consumptive. Instead, it situates remittances within a complex political economy where their developmental potential is mediated by macroeconomic stability, governance quality, and the availability of viable rural investment channels.

By foregrounding rural Zimbabwe, this research contributes to ongoing debates on migration-development linkages, capital formation, and structural transformation in fragile and post-crisis economies. The study offers policy-relevant insights into how diaspora remittances can be strategically harnessed to support productive investment, rural industrialisation, and inclusive growth. Understanding the dynamics of remittance-scapes in Zimbabwe is therefore essential for designing interventions that convert diaspora financial flows from short-term coping mechanisms into sustainable drivers of rural capital accumulation and economic resilience.

The remainder of this article is structured as follows. Section 2 reviews the relevant literature on remittances, remittance-scapes, capital formation, and rural development, highlighting key theoretical and empirical debates. Section 3 describes the research methodology employed to examine the pathways through which remittances influence capital formation in rural Zimbabwe. Section 4 presents the empirical results, which are then discussed in relation to the conceptual framework and existing literature. The final section concludes the article by summarising the main findings and outlining their policy and research implications.

Literature Review

Diaspora Remittances and Development

The relationship between migration, remittances, and development has long occupied a central position in development economics. Early neoclassical models viewed migration as an individual income-maximising decision, with remittances primarily serving as private transfers for household consumption (Todaro 1976; de Haas 2008). In contrast, the New Economics of Labour Migration (NELM) reframes remittances as part of a household risk-sharing and income diversification strategy, suggesting that remittances can relax liquidity constraints and potentially finance productive investment (Stark and Bloom 1985; Rapoport and Docquier 2006; Dawadi 2025).

Subsequent empirical work has produced mixed findings. While some studies identify remittances as catalysts for entrepreneurship and capital accumulation (Taylor 1999; Woodruff and Zenteno

2007), others argue that remittances primarily support consumption smoothing and may reduce labour supply, thereby dampening productive investment (Chami, Fullenkamp, and Jahjah 2005). These divergent outcomes underscore the importance of context, institutions, and spatial dynamics in shaping remittance use.

More recent scholarship has introduced spatial and socio-economic lenses, emphasising how remittances are embedded in local development environments. The notion of remittance-scapes builds on this literature by highlighting how geographic location, social obligations, financial infrastructure, and policy frameworks mediate the transformation of remittance inflows into development outcomes (Levitt and Lamba-Nieves 2011; Cirolia, Hall, and Nyamnjoh 2022; Guermond 2022; Kunz, Maisenbacher, and Paudel 2022; Warnecke-Berger 2022).

Remittances and Gross Capital Formation

Gross capital formation, defined as investment in fixed assets, infrastructure, and productive capacity, is a key determinant of long-term economic growth (Solow 1956; Kanu and Ozurumba 2014; Trpeski and Cvetanoska 2019; Opadeji et al. 2023). At the macroeconomic level, studies examining the impact of remittances on capital formation have yielded inconclusive results. Some cross-country analyses find that remittances contribute positively to investment and growth where financial systems are deep and institutions are strong (Giuliano and Ruiz-Arranz 2009). Conversely, in fragile and low-income economies, remittances may substitute for public investment and weaken incentives for structural reform (Gapen et al. 2009; Azizi et al. 2024).

At the micro level, evidence suggests that remittances can finance housing, agricultural inputs, and small enterprises, but these investments often remain fragmented and low in productivity (Adams and Cuecuecha 2013). In rural contexts, especially in sub-Saharan Africa (SSA), weak markets, infrastructure deficits, and limited access to complementary inputs constrain the translation of remittance inflows into meaningful capital accumulation (Ratha et al. 2018).

Diaspora Remittances and Investment in Sub-Saharan Africa

In SSA, remittances are predominantly directed toward rural households, where poverty incidence is highest and formal financial access is limited (Gupta, Pattillo, and Wagh 2009). Empirical studies from countries such as Ghana, Nigeria, and Kenya indicate that remittances improve household welfare but have a limited impact on productive investment in agriculture or rural industry (Tsegai 2007; Anyanwu and Erhijakpor 2010; Eghan and Adjasi 2023).

The literature highlights several constraints to rural capital formation, including underdeveloped rural credit markets, high transaction costs, insecure land tenure, and exposure to climatic and macroeconomic risks (Dercon and Christiaensen 2011; Linh et al. 2019; Céu and Gaspar 2024; Khan et al. 2024). As a result, remittances are frequently used for short-term consumption, social expenditures, or non-tradable assets such as housing, with limited multiplier effects in rural economies (Hagen-Zanker 2015).

Diaspora Remittances in Zimbabwe

Zimbabwe presents a distinctive case due to its prolonged economic crisis, large-scale emigration, and reliance on diaspora inflows as a survival mechanism (Crush and Tevera 2010; Pasura 2012). Studies consistently show that remittances have played a critical role in sustaining household livelihoods during periods of hyperinflation, currency instability, and declining real incomes (Bracking and Sachikonye 2010; Makina 2010; Combes and Ebeke 2011; Khan 2025).

At the household level, remittances in Zimbabwe are primarily used for food security, education, healthcare, and housing construction, particularly in rural areas (Sachikonye 2011; Nyikahadzoi et al. 2019; Ndhlovu 2020). While housing investment is often classified as capital formation, its productive impact is limited in the absence of complementary economic activity (Maphosa 2007; Mazwi 2022). Empirical evidence suggests that remittance-financed investment in agriculture and rural enterprises remains minimal, largely due to structural constraints rather than household preferences (Alhassan, Maswana, and Inaba 2025; Yoda 2025).

Macroeconomic instability has further weakened the investment potential of remittances (Ratha and Mohapatra 2007; Elorabi, Ishak, and Maher 2024). Persistent inflation, currency regime shifts, and policy uncertainty have discouraged long-term planning and eroded savings (Greenspan 2004; Ncube and Brixiová 2015; Iddrisu et al. 2025). In rural Zimbabwe, insecure land tenure arrangements following the fast-track land reform programme have also reduced incentives for fixed capital investment in agriculture (Matondi and Dekker 2011; Scoones et al. 2011; Mkodzongi and Lawrence 2019; Shonhe 2019).

Remittances, Institutions, and Rural Capital Formation in Zimbabwe

Institutional quality plays a decisive role in determining whether remittances are associated with capital formation (Lartey and Mengova 2016; Mohammed and Karagöl 2023). Studies on Zimbabwe highlight weak financial intermediation, limited diaspora investment instruments, and the absence of targeted rural development policies as key barriers (Kapur 2005; 2010; Muzapu and Havadi 2021). Informal remittance channels, while efficient for household transfers, further limit the mobilisation of remittances into formal investment and savings systems (Guermond 2022; Warnecke-Berger 2022; Nanziri and Mwale 2023). Spatial inequalities also shape remittance outcomes. Urban areas attract a disproportionate share of remittance-funded investment due to better infrastructure, market access, and perceived security of returns (Prokhorova 2017; Saha et al. 2024; Yunus et al. 2025; Islam and Baida 2026). Consequently, remittance-scapes in Zimbabwe tend to reinforce rural marginalisation rather than promote balanced capital formation (Guermond 2022; Menon 2025).

Synthesis and Research Gap

The literature demonstrates that while diaspora remittances are vital for household welfare and macroeconomic stability in Zimbabwe, their contribution to gross capital formation in rural areas remains weak and inconsistent. Existing studies often focus on consumption impacts or macroeconomic aggregates, with limited attention to the spatial, institutional, and investment ecosystem dynamics that shape remittance use in rural settings. This study addresses this gap

by applying the remittance-scapes framework to analyse how diaspora remittances interact with rural investment environments in Zimbabwe. By focusing explicitly on gross capital formation, the research advances understanding of the conditions under which remittances can transition from coping mechanisms to engines of rural structural transformation.

Research Methodology

Research Design

This study adopts a systematic literature review guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Page and Moher 2017; Parums 2021). The PRISMA approach was selected to ensure transparency, reproducibility, and methodological rigour in synthesising empirical and theoretical evidence on the impact of diaspora remittances on gross capital formation in rural areas, with a specific focus on Zimbabwe (Sunge and Mudzingiri 2023). Given the fragmented and context-specific nature of remittance literature, a systematic review enables the structured identification, screening, and synthesis of relevant studies across disciplines, including development economics, migration studies, rural development, and African studies.

Search Strategy

A comprehensive literature search was conducted across multiple electronic databases to capture peer-reviewed and high-quality grey literature. The databases included Scopus, Web of Science, EconLit, ScienceDirect, JSTOR, and Google Scholar. In addition, institutional repositories and policy databases from the World Bank, International Monetary Fund (IMF), African Development Bank (AfDB), Reserve Bank of Zimbabwe (RBZ), and Zimbabwe National Statistics Agency (ZIMSTAT) were consulted to capture country-specific evidence. The search was performed using a combination of keywords and Boolean operators. Core search strings included:

- “diaspora remittances” OR “international remittances”
- AND “gross capital formation” OR “capital accumulation” OR “investment”
- AND “rural development” OR “rural investment”
- AND “Zimbabwe” OR “sub-Saharan Africa”.

Search terms were adapted slightly across databases to accommodate differences in indexing and search functionalities. Reference lists of selected articles were manually reviewed to identify additional relevant studies.

Eligibility Criteria

Study selection was guided by predefined inclusion and exclusion criteria to ensure relevance and quality, as shown in Table 1 below.

Table 1. Inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
Peer-reviewed journal articles, working papers, and institutional reports.	Studies focusing exclusively on internal remittances.
Studies published in English.	Articles addressing remittances without reference to investment, capital formation, or productive use.
Empirical or theoretical studies examining remittances, investment, or capital formation.	Non-scholarly opinion pieces, blog posts, and media articles.
Studies focusing on Zimbabwe or comparable SSA rural contexts.	Studies with insufficient methodological detail or unclear data sources.
Publications released between 2000 and 2024 (intensified migration and remittance flows in Zimbabwe).	

Source: author's compilation.

Study Selection Process

The study selection process followed the four PRISMA stages: identification, screening, eligibility, and inclusion. During the identification stage, all retrieved records were imported into a reference management system, and duplicates were removed. Titles and abstracts were then screened to assess relevance to the research objectives. Full-text articles were subsequently reviewed for eligibility based on the inclusion and exclusion criteria. Studies that met all criteria were included in the final synthesis. Disagreements regarding study inclusion were resolved through iterative review and consensus-building.

Data Extraction

A structured data extraction template was developed to ensure consistency across studies. Extracted information included:

- Author(s) and year of publication;
- Study location and rural focus;
- Data sources and sample characteristics;
- Methodological approach (quantitative, qualitative, or mixed methods);
- Measures of remittances and gross capital formation;
- Key findings related to rural investment and capital accumulation;
- Identified institutional, policy, or macroeconomic constraints.

This approach facilitated systematic comparison and thematic synthesis across studies.

Quality Assessment

The quality assessment of included studies was conducted in line with the principles of the PRISMA framework to ensure methodological rigour, transparency, and reproducibility. Given

the heterogeneity of the evidence base, an adapted appraisal framework was applied across quantitative, qualitative, and policy-oriented studies.

Quantitative studies were evaluated based on data reliability, sample representativeness, measurement validity, and econometric robustness, with particular attention to the treatment of endogeneity, omitted variable bias, and model specification. Qualitative studies were assessed for analytical depth, contextual validity, methodological transparency, and coherence between evidence and interpretation. Policy reports and grey literature were appraised according to the credibility of data sources, methodological clarity, and the institutional reliability of the issuing bodies.

The quality assessment process was directly integrated into the study selection procedure. During the screening phase, studies were required to meet minimum methodological standards to satisfy the inclusion criteria (Table 1). Specifically, studies that lacked sufficient transparency in methods, relied on unverifiable data sources, or exhibited significant analytical weaknesses were excluded at the full-text review stage.

Following inclusion, each study was assigned a quality rating (high, moderate, or low) based on the appraisal criteria. These ratings informed the synthesis by guiding the weighting of evidence: high-quality studies were prioritised in the interpretation of findings, while studies of moderate quality were used to support broader patterns. Studies assessed as low quality were retained only where they provided unique contextual insights, but were interpreted with caution.

Data Synthesis

Given the heterogeneity of study designs, data sources, and outcome measures, a narrative synthesis approach was employed rather than a formal meta-analysis. Findings were synthesised thematically, focusing on patterns relating to remittance utilisation, rural investment behaviour, institutional constraints, and spatial dynamics. The concept of remittance-scapes was used as an analytical lens to integrate empirical findings within broader socio-economic and geographic contexts.

PRISMA Flow Process

The PRISMA flow process, illustrated in Figure 1, documents the number of records identified, screened, excluded, and included at each stage of the review to enhance the transparency and replicability of the selection process.

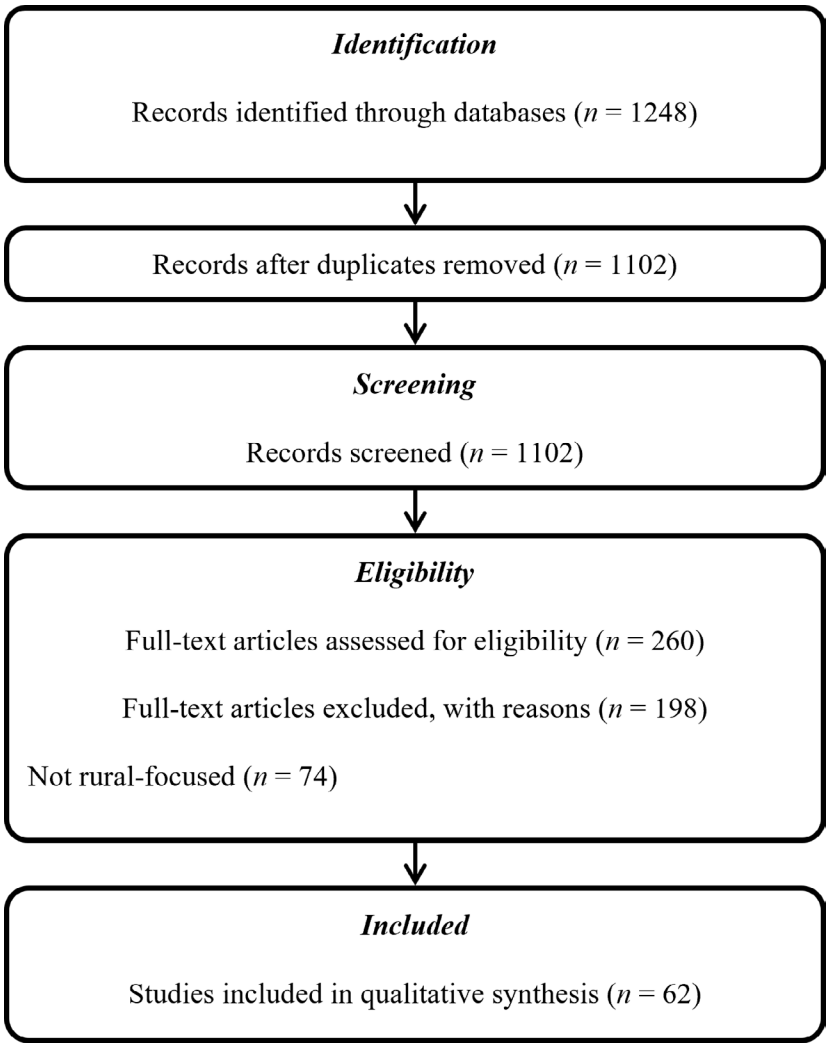

Figure 1. PRISMA flow diagram
Source: author's compilation.

Study Selection

A total of 41 studies were excluded at the full-text review stage due to methodological weaknesses identified during the quality appraisal process. To enhance transparency, the primary reasons for exclusion were systematically recorded and are summarised in Table 2.

Studies were excluded where they failed to meet minimum quality thresholds based on the appraisal criteria aligned with PRISMA guidelines. The most common reasons for exclusion included: (i) insufficient methodological transparency, (ii) reliance on unverifiable or anecdotal data sources, (iii) weak or inappropriate analytical methods, and (iv) a lack of relevance to the study's conceptual framework, for example, no clear linkage between remittances and rural capital formation.

Table 2. Reasons for exclusion at full-text stage (*n* = 41)

Reason for Exclusion	Description	Number of Studies
Methodological opacity	Inadequate description of data collection or analytical procedures	12
Weak analytical rigor	Absence of systematic analysis or inappropriate methods	9
Unverifiable data sources	Reliance on anecdotal evidence or non-credible data	8
Conceptual misalignment	No clear focus on remittances and rural capital formation	7
Data limitations	Insufficient or outdated data undermining reliability	5
Total		41

Note: Reasons for exclusion at the full-text stage are reported to ensure transparency and reproducibility, consistent with PRISMA recommendations.

Source: author's compilation.

Ethical Considerations

As this study relied exclusively on secondary data from published sources, no ethical approval was required. However, all sources were appropriately cited, and care was taken to accurately represent original findings.

Methodological Limitations

While the PRISMA approach enhances systematic rigour, the review is subject to limitations. These include potential publication bias, language restrictions, and uneven availability of rural-specific data for Zimbabwe. Nevertheless, the methodology provides a robust foundation for synthesising existing knowledge and identifying research gaps.

Presentation of results

Following the PRISMA screening process, a total of 62 studies were included in the final qualitative and thematic synthesis. These studies comprise peer-reviewed journal articles (71%), institutional and policy reports (21%), and working papers (8%). The evidence base reflects a mix of quantitative, qualitative, and mixed-methods approaches, highlighting the multidisciplinary nature of remittance research in Zimbabwe and comparable SSA contexts. Table 3 summarises the key characteristics of the included studies.

Table 3. Characteristics of included studies (*n* = 62)

Characteristic	Category	Number of Studies	Percentage (%)	Quality Rating*
Study Type	Peer-reviewed articles	44	71	High
	Policy & institutional reports	13	21	Moderate
	Working papers	5	8	Moderate

Characteristic	Category	Number of Studies	Percentage (%)	Quality Rating*
Methodology	Quantitative	27	44	High
	Qualitative	18	29	Moderate
	Mixed methods	17	27	High
Geographic Focus	Zimbabwe-specific	31	50	Moderate
	Sub-Saharan Africa (comparative)	31	50	High
Sectoral Focus	Rural livelihoods & agriculture	36	58	Moderate
	Rural enterprise & infrastructure	26	42	High

Note: Quality ratings (high, moderate, low) are assigned based on aggregated performance against the appraisal framework aligned with PRISMA principles. Ratings reflect typical methodological strengths observed within each category. High: Strong data credibility, robust methodology, and clear analytical frameworks; for example, peer-reviewed and mixed-method studies with triangulation. Moderate: Adequate rigour but some limitations in data, scope, or transparency; for example, policy reports and qualitative case studies. Low: Significant methodological limitations (excluded or minimally used in synthesis; not prominent in final sample).

Source: author's compilation.

While Table 2 presents aggregate quality trends by study characteristics, individual study ratings were assigned separately and used to guide evidence weighting in the synthesis.

The balanced inclusion of Zimbabwe-specific and comparative studies strengthens the contextual relevance while allowing broader inferential insights. To enhance comparability across heterogeneous studies, categorisation criteria were standardised. Reported uses of remittances distinguish between general mentions and empirically measured primary uses. Similarly, outcome classifications for capital formation were harmonised by combining statistical significance (for quantitative studies) with strength and consistency of evidence (for qualitative and mixed-methods studies). Constraint frequencies were further adjusted using quality-weighted measures to reflect differences in methodological rigour.

Patterns of Remittance Utilisation in Rural Zimbabwe

Evidence from the reviewed studies indicates that remittances in rural Zimbabwe are predominantly directed toward consumption and basic welfare needs, with more limited allocation to productive investment. As shown in Table 4, 79% of studies report food consumption and basic household needs as a key use of remittances, while 68% identify expenditure on education and health. However, these figures reflect the frequency of reporting across studies rather than measured expenditure shares. Where studies use household survey data to quantify remittance allocation, consumption-related uses remain dominant (61% of measured allocations), reinforcing the interpretation that remittances primarily function as a short-term welfare stabilisation mechanism rather than a direct driver of capital accumulation.

Asset-related uses are less common and more constrained in scale. Housing construction appears in 54% of studies, but is generally characterised as non-productive asset accumulation with limited spillover into income-generating activity. Productive allocations such as agricultural inputs (29%), rural enterprises (21%), and savings or insurance mechanisms (17%) are comparatively

marginal, suggesting weak financial intermediation of diaspora inflows into rural investment channels. Overall, the evidence indicates that while remittances contribute meaningfully to household welfare and human capital formation, their translation into productive rural capital formation remains limited and structurally constrained.

Table 4. Reported uses of remittances in rural Zimbabwe

Use Category	Share of Studies Reporting Use (%)*	Primary Use (Quantitative Evidence %)**	Developmental Implication
Food consumption & basic needs	79	61	Short-term welfare support
Education & health	68	49	Human capital formation
Housing construction	54	38	Limited productive spillovers
Agricultural inputs & equipment	29	22	Modest capital formation
Rural enterprises & SMEs	21	16	Potential but constrained investment
Financial savings & insurance	17	12	Weak financial intermediation

Notes: * "Share of studies reporting use" refers to the proportion of included studies that mention a given use category, regardless of whether it is a primary or secondary use. ** "Primary use (quantitative evidence)" includes only studies that empirically measure remittance allocation (for example, household surveys, expenditure shares) and identify the category as a dominant or statistically significant use.

Source: author's compilation.

Remittances and Gross Capital Formation Outcomes

The relationship between remittance inflows and rural capital formation is mixed and highly context-dependent. As summarised in Table 5, only 22 of the 62 studies (35%) provide evidence of a statistically significant or qualitatively robust positive effect on productive investment outcomes. These studies typically document small-scale investments in livestock, farming tools, and informal micro-enterprises.

However, the classification of effects is based on a harmonised outcome framework that combines statistical significance (for quantitative studies) and consistency/strength of evidence (for qualitative studies). Within this framework, 26 studies report insignificant or weak effects, where remittances are largely absorbed by consumption with limited investment conversion. A further 14 studies identify negative or displacement effects, including reduced labour supply and increased dependency dynamics within rural households. Taken together, the evidence suggests that remittances alone are insufficient to generate sustained capital accumulation. Even when positive effects are observed, they tend to be fragmented, small-scale, and vulnerable to macroeconomic instability and environmental shocks.

Table 5. Evidence on remittances and capital formation

Outcome Category	Number of Studies	Definition of Category*	Key Findings
Positive effect on rural capital formation	22	Statistically significant ($p < 0.05$) relationship **or** strong qualitative evidence of sustained productive investment	Investments in farming tools, livestock, micro-enterprises
Insignificant or weak effect	26	No statistically significant relationship **or** evidence of limited, irregular, or consumption-dominated use	Remittances largely absorbed by consumption
Negative or displacement effect	14	Evidence of statistically significant negative effects **or** consistent qualitative findings of disincentives (e.g., labour withdrawal, dependency)	Reduced labour supply, dependency effects

Notes: * Categorisation is based on study-specific definitions of outcomes, harmonised using a common framework (Quantitative studies: statistical significance and direction of effect. Qualitative/mixed-methods: strength, consistency, and depth of evidence regarding productive investment outcomes).

Source: author's compilation.

Institutional and Macroeconomic Constraints

Across the reviewed literature, a strong consensus emerges regarding the structural constraints that limit the developmental impact of remittances. Table 6 shows that inflation and currency instability are the most frequently cited constraints (76%), followed by weak rural financial markets (63%), insecure land tenure (58%), inadequate infrastructure (55%), and policy uncertainty (47%). Importantly, these frequencies reflect quality-adjusted citation counts**,** ensuring that higher-quality studies exert greater influence on the aggregated pattern. This weighting strengthens the robustness of the identified constraints, particularly in relation to macroeconomic instability and institutional weakness.

These constraints collectively shape the "remittance-scape" of rural Zimbabwe by channelling diaspora inflows toward low-risk and immediately consumptive uses rather than long-term productive investment. High inflation erodes savings and investment value, while weak financial systems and insecure land tenure reduce incentives for capital formation. As a result, remittances tend to function as short-term survival support rather than instruments of structural transformation.

Table 6. Identified constraints to remittance-financed capital formation

Constraint	Frequency of Citation (%)*	Quality-Weighted Frequency (%)**	Impact on Capital Formation
Inflation & currency instability	76	81	Erosion of savings and investment value
Weak rural financial markets	63	66	Limited investment channels
Insecure land tenure	58	61	Discourages fixed capital investment
Poor rural infrastructure	55	57	Raises transaction costs
Policy uncertainty	47	52	Undermines investor confidence

Notes: * "Frequency of citation" refers to the proportion of included studies that identify the constraint. ** "Quality-weighted frequency" adjusts counts using study quality ratings (high = 2, moderate = 1, low = 0.5), ensuring that more robust studies have greater influence on reported patterns.

Source: author's compilation.

Spatial Dimensions of Remittance Investment

The spatial analysis reveals a pronounced urban bias in remittance-financed investments (Table 7). Studies indicate that diaspora households often prefer to invest in urban real estate, retail trade, and services due to better infrastructure, stronger markets, and higher perceived returns.

Table 7. Spatial allocation of remittance-financed investments

Location	Share of Reported Investments (%)
Urban areas	64
Peri-urban areas	21
Rural areas	15

Source: author's compilation.

This spatial imbalance reinforces rural underdevelopment and limits the role of remittances in promoting balanced gross capital formation.

Synthesis of Key Findings

Overall, the results demonstrate that while diaspora remittances are vital for household survival and macroeconomic stability in Zimbabwe, their impact on rural gross capital formation is limited and conditional. Remittance outcomes are shaped by a complex interaction of household priorities, institutional quality, spatial investment opportunities, and macroeconomic conditions. The remittance-scapes framework reveals that remittances tend to reproduce existing structural inequalities rather than transform rural investment landscapes.

Remittance-scapes, Capital Formation and Rural Development Frameworks

The concept of *remittance-scapes* provides an analytical advancement over conventional remittance-growth or remittance-consumption frameworks by conceptualising diaspora financial flows as embedded within interconnected transnational, institutional, and spatial systems rather than as isolated household-level transfers. While alternative approaches typically focus on either macroeconomic effects (for example, growth regressions) or micro-level household uses, the remittance-scapes framework integrates both levels and explicitly captures the relational pathways through which remittances are transformed, redirected, or absorbed within rural economies.

Specifically, the framework adds three analytical contributions. First, it identifies mediating mechanisms that include financial intermediation, governance quality, household decision-making structures, and the investment climate, which collectively determine whether remittances are consumed, saved, or invested. Second, it highlights spatial dynamics, showing how remittances flow unevenly across rural, peri-urban, and urban spaces, reinforcing territorial inequalities. Third, it incorporates feedback loops, whereby macroeconomic instability and institutional weakness not only constrain

investment outcomes but also reshape future remittance behaviour by increasing precautionary transfers and reducing long-term investment confidence.

These elements are not explicitly captured in alternative frameworks such as NELM, which primarily emphasises household utility maximisation under income risk. In contrast, remittance-scapes provides a systems-level explanatory lens linking micro decisions, meso-level institutions, and macroeconomic conditions.

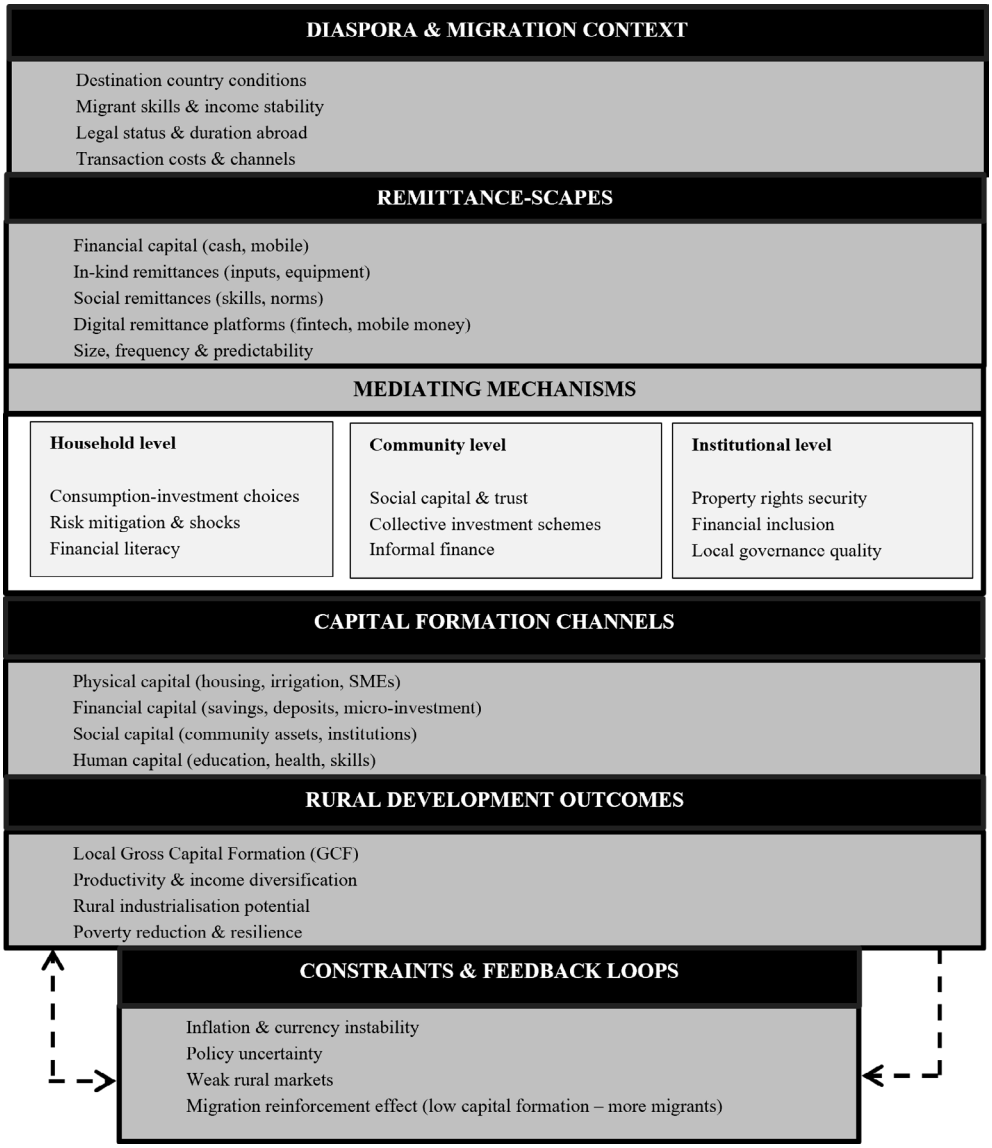

Figure 2. Conceptual mapping of remittance-scapes and capital formation pathways in rural Zimbabwe
Source: author's compilation.

Discussion of Findings

The findings of this systematic review reveal that diaspora remittances in rural Zimbabwe are predominantly used for consumption and basic household needs, with limited translation into productive investment and gross capital formation. As illustrated in Figure 2, this outcome is shaped by the interaction between remittance inflows and mediating institutional and household-level mechanisms, particularly weak financial intermediation, constrained investment opportunities, and survival-oriented household decision-making. In the absence of effective financial systems, remittances are absorbed into immediate consumption rather than channelled into savings or investment pathways.

This pattern is consistent with earlier studies that characterise remittances in fragile and crisis-prone economies as survival mechanisms rather than development finance (Chami, Fullenkamp, and Jahjah 2005; Makina 2010). Within the remittance-scapes framework, this reflects a feedback loop between macroeconomic instability and household behaviour, where persistent inflation and uncertainty reinforce precautionary consumption patterns and discourage long-term capital formation.

These results align with NELM, which conceptualises remittances as instruments for income smoothing and risk mitigation in the absence of formal insurance and credit markets (Stark and Bloom 1985). However, Figure 2 extends this logic by demonstrating that in Zimbabwe's context, macroeconomic instability and institutional fragmentation act as constraining feedback mechanisms, limiting the transition from risk mitigation to productive investment. Similar dynamics are observed in Ghana and Nigeria, where weak institutional environments mediate and often suppress the developmental potential of remittances (Anyanwu and Erhijakpor 2010; Adams and Cuecuecha 2013).

Housing Investment and Limited Capital Formation Spillovers

Within the remittance-scapes framework (Figure 2), housing investment represents a dominant asset accumulation channel, but one that is largely disconnected from productive economic circuits. Housing construction emerges as the most common form of physical asset accumulation financed by remittances in rural Zimbabwe; however, its developmental impact remains limited due to weak linkages with labour markets and productive sectors.

This reflects a spatial lock-in effect, where remittances are converted into immobile assets that reinforce household security rather than generating income flows. The finding corroborates evidence from SSA showing that remittance-financed housing rarely generates sustained employment or productivity gains beyond the construction phase (Gupta, Pattillo, and Wagh 2009).

In Zimbabwe, this pattern is reinforced by a feedback loop between macroeconomic instability and asset preference: in high-inflation environments, households rationally shift remittances into real estate as a store of value. As shown in Figure 2, this reduces liquidity available for productive investment while reinforcing consumption-and-asset pathways rather than enterprise development (Gapen et al. 2009; Azizi et al. 2024).

Weak Linkages between Remittances and Productive Rural Investment

Only a minority of studies reviewed report a positive association between remittances and productive capital formation in rural Zimbabwe. In Figure 2, this corresponds to the investment conversion pathway, where remittances pass through financial intermediation and are transformed into productive assets. However, this pathway remains weak and fragmented.

Where such effects exist, they are largely confined to small-scale investments in livestock, agricultural inputs, and micro-enterprises. These outcomes are constrained by institutional bottlenecks and limited financial mediation, which prevent the scaling of investment activities. This finding aligns with Taylor's (1999) argument that remittance impacts depend heavily on complementary public investment and functioning markets.

The framework further highlights a reinforcing feedback loop: weak financial systems reduce investment returns, which in turn discourages future productive allocation of remittances. Consistent with Giuliano and Ruiz-Arranz (2009), deeper financial systems are critical for converting remittances into growth-enhancing capital formation.

Macroeconomic Instability as a Binding Constraint

Macroeconomic instability emerges as the most significant structural constraint in Figure 2, operating through a macro-level feedback loop that continuously reshapes remittance behaviour. High inflation, currency volatility, and policy inconsistency reduce the real value of remittances and increase household preference for immediate consumption or foreign-currency hoarding.

This dynamic reinforces short-termism in financial decision-making and weakens long-term investment planning. As shown in the framework, macroeconomic instability not only constrains outcomes but also feeds back into the system by altering remittance allocation behaviour over time.

These findings reinforce macroeconomic literature identifying instability as a deterrent to private investment in developing economies (Ncube and Brixiová 2015) and support Chami, Fullenkamp, and Jahjah (2005), who argue that remittances may become growth-neutral or even counterproductive under distorted macroeconomic conditions.

Institutional and Land Tenure Constraints in Rural Zimbabwe

Institutional constraints, particularly land tenure insecurity, operate in Figure 2 as part of the institutional mediation layer that determines whether remittances can be transformed into fixed capital investment. In rural Zimbabwe, uncertainty surrounding land rights reduces incentives for long-term agricultural investment, particularly in irrigation, mechanisation, and agro-processing (Scoones et al. 2011).

This reflects a mechanism of investment deferral, where households rationally avoid capital-intensive investments due to weak property rights and high policy uncertainty. The absence of diaspora-targeted investment instruments further limits the institutional conversion of remittances into collective development assets (Ratha et al. 2018). As a result, remittance flows

remain atomised at the household level, reinforcing consumption pathways rather than enabling coordinated capital formation.

Spatial Bias and the Reinforcement of Rural Marginalisation

A key spatial dynamic identified in Figure 2 is the uneven distribution of remittance-financed investment across geographic spaces. The evidence shows a pronounced urban and peri-urban bias, with rural areas receiving fewer productive investments. This reflects a spatial filtering mechanism, whereby remittances flow toward areas with stronger infrastructure, better market access, and lower perceived risk. Urban centres thus act as investment absorbers, while rural areas remain structurally marginalised.

From a remittance-scapes perspective, this spatial pattern is not incidental but structurally produced through the interaction of institutional capacity, infrastructure disparities, and investment risk perception. Similar spatial inequalities observed in Kenya and Senegal confirm that remittances often reinforce rather than reduce regional disparities (Levitt and Lamba-Nieves 2011). In Zimbabwe, this spatial bias weakens the capacity of remittances to influence rural capital formation and inclusive structural transformation.

Comparative Remittance Dynamics in Sub-Saharan Africa

The comparative evidence presented in Table 8 highlights that Zimbabwe's weak remittance–capital formation link is not an isolated or exceptional case, but rather aligns with a broader pattern observed in structurally constrained economies within SSA. Countries such as Nigeria and Zimbabwe share similar macro-financial vulnerabilities, including high inflation, exchange rate instability, and underdeveloped financial intermediation systems. In these contexts, remittances are predominantly absorbed by household consumption needs, with limited translation into savings or productive investment. This suggests that the developmental impact of remittances is strongly mediated by the stability and efficiency of domestic financial and macroeconomic institutions.

Table 8. Comparative profile of remittance use and capital formation conditions in selected SSA countries

Country	Remittance Importance	Financial Intermediation	Macroeconomic Stability	Dominant Use of Remittances	Remittance to Capital Formation Link	Key Structural Constraints
Zimbabwe	High (relative to GDP; major external inflow)	Weak–moderate; banking mistrust, liquidity constraints, uneven access	Very weak; currency instability and inflation episodes	Mainly consumption (food, health, education), survival support	Weak	Currency volatility, informalisation, limited credit markets, policy uncertainty
Ghana	Moderate–high	Moderate; improving digital finance and banking access	Moderate stability with occasional fiscal pressure	Mixed: consumption + small business/ informal investment	Moderate	High cost of credit, inequality, rural financial exclusion

Country	Remittance Importance	Financial Intermediation	Macroeconomic Stability	Dominant Use of Remittances	Remittance to Capital Formation Link	Key Structural Constraints
Kenya	Moderate	Strong; advanced mobile money ecosystem (e.g., M-Pesa)	Relatively stable macro environment	Consumption + strong SME and microenterprise investment	Moderate–strong	Income inequality, urban-rural divide, high youth unemployment
Nigeria	Very high (largest remittance receiver in SSA)	Weak–moderate; banking system large but inefficient	Weak; exchange rate volatility and inflation	Mostly consumption, housing, education; limited productive investment	Weak–moderate	FX controls, inflation, infrastructure gaps, capital flight pressures
Senegal	Moderate	Moderate; improving but still limited rural access	Relatively stable	Consumption + migration-financed housing investment	Moderate	Rural poverty, limited industrial base, dependence on external flows

Source: author's compilation.

In contrast, economies such as Kenya demonstrate more favourable conditions for converting remittance inflows into capital formation, largely due to stronger financial inclusion mechanisms, particularly mobile money platforms and relatively greater macroeconomic stability. Ghana and Senegal occupy an intermediate position, where remittances contribute to both consumption and small-scale entrepreneurial activity, but structural constraints still limit large-scale investment effects. Overall, the table supports a continuum perspective in which the remittance–development nexus is conditioned by institutional quality and financial infrastructure, thereby reinforcing the interpretation that Zimbabwe's experience reflects a fragility-driven outcome rather than a country-specific anomaly.

Limitations of the Remittance-Scapes Framework

While the remittance-scapes framework provides an integrated multi-level explanation of diaspora financial flows, it has certain limitations. First, it relies on secondary synthesis and therefore cannot fully capture micro-level behavioural heterogeneity across households. Second, the framework aggregates complex spatial and institutional dynamics that may vary significantly across districts and livelihood systems. Third, the operationalisation of feedback loops remains largely conceptual rather than quantitatively modelled. Future research could address these limitations by applying spatial econometric methods or utilising longitudinal household data to empirically test the dynamic interactions proposed in Figure 2.

Conclusion

This study set out to examine the relationship between diaspora remittances and gross capital formation in rural Zimbabwe through a systematic review guided by the PRISMA framework

and analysed using the remittance-scapes lens. The findings demonstrate that while remittances constitute a critical lifeline for rural households and a stabilising source of foreign inflows for the national economy, their contribution to sustained rural capital formation remains limited and highly contingent on structural and institutional conditions.

The evidence shows that remittances in rural Zimbabwe are predominantly directed toward consumption smoothing, social expenditures, and housing construction, with only marginal investment in productive assets such as agricultural equipment, agro-processing, and rural enterprises. Although housing investment expands household asset portfolios, it offers limited productive spillovers in the absence of complementary economic activity. This pattern reflects a broader development paradox in which substantial diaspora inflows coexist with persistently low levels of rural fixed capital accumulation.

The study further highlights macroeconomic instability, weak rural financial intermediation, insecure land tenure, and spatial investment biases as binding constraints that inhibit the transformation of remittances into productive capital. These constraints shape Zimbabwe's remittance-scapes by channelling diaspora resources toward low-risk, non-tradable assets and urban investment opportunities, thereby reinforcing existing rural–urban inequalities. Collectively, the findings confirm that remittances cannot substitute for coherent macroeconomic policy, institutional reform, or public investment in rural infrastructure.

Implications for Research

The findings contribute to the broader remittance-development debate by demonstrating that remittances are neither inherently developmental nor inherently detrimental. Instead, their impact on gross capital formation is contingent upon macroeconomic stability, institutional quality, and spatial investment opportunities. The evidence from rural Zimbabwe challenges optimistic narratives that position remittances as substitutes for public investment or development finance.

The findings point to several important avenues for future research. First, there is a need for micro-level empirical studies that explicitly measure the contribution of remittances to different components of gross capital formation in rural Zimbabwe, including agricultural capital, rural infrastructure, and enterprise development. Disaggregated analyses by gender, land tenure status, and remittance channel would provide deeper insights into heterogeneous investment behaviours.

Second, future research should move beyond household-level analysis to examine collective and meso-level investment mechanisms, such as diaspora cooperatives, community investment funds, and public–private partnerships. Understanding how remittances can be pooled and leveraged for shared infrastructure and value-chain development remains an underexplored area.

Third, longitudinal and quasi-experimental studies are required to assess how changes in macroeconomic stability, financial inclusion, and land tenure security alter remittance investment behaviour over time. Such approaches would strengthen causal inference and inform evidence-based policy design.

Finally, applying the remittance-scapes framework across different rural regions and comparing Zimbabwe with other fragile and post-crisis economies in sub-Saharan Africa would enhance the generalisability of findings and contribute to theory-building in migration–development scholarship.

Implications for Policy and Practice

From a policy and practice perspective, the findings underscore the need to establish an enabling environment that transforms diaspora remittances from primarily survival-oriented transfers into drivers of rural capital formation and structural transformation. Central to this is the provision of macroeconomic stability – namely, low inflation, currency predictability, and policy consistency – alongside reforms in land tenure security and the development of inclusive rural financial markets. Without these foundational conditions, remittances are likely to remain largely confined to short-term coping functions rather than contributing to sustained investment and development. These findings reinforce earlier arguments that complementary policy interventions are essential to unlock the developmental potential of diaspora finance (Giuliano and Ruiz-Arranz 2009; Ratha et al. 2018).

Strengthening rural financial systems is equally critical. Expanding access to savings instruments, investment products, and affordable credit can enable households to leverage remittances into scalable productive activities. Financial innovation, including diaspora-linked rural investment funds and digital financial platforms, offers practical pathways for improving remittance intermediation.

Land tenure security remains a central concern for rural investment in Zimbabwe. Policy reforms that clarify and protect land-use rights would significantly enhance incentives for remittance-financed agricultural and agro-industrial investment. In parallel, targeted rural infrastructure development in irrigation, transport, and energy would reduce transaction costs and improve the viability of productive rural enterprises.

Finally, engaging the Zimbabwean diaspora through structured investment vehicles, transparent governance arrangements, and trust-building measures can help align diaspora capital with national and rural development priorities. Rather than viewing remittances as private flows beyond policy influence, governments and development partners should recognise them as strategic resources that require supportive institutions and coherent policy frameworks.

In conclusion, diaspora remittances remain indispensable to rural livelihoods in Zimbabwe but have yet to fulfil their potential as catalysts for gross capital formation and rural structural transformation. This study demonstrates that the developmental impact of remittances is not inherent but constructed through the interaction of households, institutions, and spatial investment environments. Harnessing remittances for sustainable rural development therefore requires a shift from remittance dependence toward remittance-enabled development, grounded in macroeconomic stability, institutional reform, and inclusive rural investment strategies.

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Comparative Economic Research. Central and Eastern Europe
Volume 29 Number 3, 2026
https://doi.org/10.18778/1508-2008.29.25

From Innovation to Sustainable Competitiveness: Enhancing the Role of Education and the Green-Digital Transition in Central and Eastern Europe

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Funding information: This work was supported by the START GRANT Programme – an integration grant for teaching and research staff of the West University of Timișoara (Grant Agreement No. 001352/14.01.2025), as well as by the University of Lodz, Lodz, Poland.
The percentage share of the Authors in the preparation of the work is: G.G.N. – 20.00%, M.C. – 20.00%, T.D. – 20.00%, A.I. – 20.00%, F.C.B. – 20.00%.
Conflicts of interests: None.
Ethical considerations: The Authors assure of no violations of publication ethics and take full responsibility for the content of the publication.
Received: 23.03.2026. Verified: 29.04.2026. Accepted: 16.07.2026

Abstract

Technological innovation and digital transformation are increasingly viewed as key drivers of competitiveness and environmental transformation in Central and Eastern Europe (CEE). Yet the extent to which innovation-driven performance also translates into broader sustainability improvements remains insufficiently understood. The current study focuses on determining the link between innovation capabilities, education system, digitization, and sustainable performance for CEE countries in the time frame of 2017 to 2024. Panel data were collected from a multivariate panel dataset created from the European Innovation Scoreboard, with sustainable performance evaluated by the environmental sustainability index, technology for the environment, and PM2.5 emissions. To guarantee the reliability of the results, several approaches for estimating the relationships between variables were used, such as random effects panel regression, pooled OLS estimation with Driscoll-Kraay and panel-corrected standard errors, and robust regression with Huber and biweight iterations. In addition, structural equation modeling (SEM) is employed to identify latent interdependencies among innovation, digitalization, education, and sustainability indicators. The results indicate that stronger innovation capacity and digitalization are associated with improvements in sustainability outcomes of CEE countries, with education playing a decisive role in enhancing this performance. Environmental improvements are even more noticeable in countries that have higher degrees of green and digital innovations. The present research makes a valuable contribution to existing literature in the field, as it presents a comprehensive examination of the innovation-greening-digitalization relationship in CEE countries by using an eclectic approach of multiple econometric and SEM analysis techniques.

Keywords: technological innovation, digitalization, environmental sustainability, education, econometric modeling

JEL: C21, O31, Q56, R12

Introduction

Technological innovation and digitalization have emerged as major pillars of economic change in the globalized digital economy, especially in response to increased levels of competitive pressures, green transition imperatives, and structural asymmetries between European economies. Innovation is a major asset in recent times, not only as a means of improving productivity and market dynamism but also as a strategic tool to improve environmental sustainability and resilience. This discussion has particular relevance with regard to Central and Eastern Europe (CEE), considering the fact that these countries face the challenge of striking the right balance between the pursuit of innovation and digitalization, on the one hand, and the need to meet the imperatives of sustainability which are part of the broader European policy agenda on the other hand. The relevance of this issue cannot be overemphasized, particularly with regard to the CEE economies, considering the fact that despite the higher levels of integration of these economies into the European and global value chains, significant disparities exist with regard to the levels of innovation, digitalization, institutional development, and market sophistication, among others. Thus, while the impact of innovation on development cannot be linear, with the former influencing the latter in many dimensions, such as capabilities, export performance, labor, and spillovers to neighboring countries, technological progress may impact development in many dimensions. At the same time, it is not evident that all economies benefit equally from such phenomena, as the benefits of innovation and digitalization may depend on the level of green, financial, and organizational capabilities accumulated in these economies.

From this existing literature, significant insights into these developments can be derived, although they remain fragmented in several respects. First, a significant amount of the literature confirms that digitalization and innovation are key drivers of enhanced sustainability in terms of cleaner production, green innovation, and environmental performance. Second, a series of contributions emphasizes their impact on competitiveness, renewal of firms, and performance enhancement in terms of digitalization, Industry 4.0, and innovation strategies. Yet, in most of these contributions, these dynamics are analyzed in isolation from each other, and environmental and economic effects are rarely analyzed in a unified manner. Moreover, whereas a large body of this literature is based on firm-level or cross-country analyses or broader international samples, there is a relatively limited amount of research on the specific case of CEE.

Finally, this literature still devotes relatively little attention to two key issues that are of significant concern to this particular region. First, the focus on spillovers and international border effects remains limited, especially in light of the strong interdependencies in terms of trade, policies, and geography, which define CEE. This points to the fact that, for instance, innovation and digitalization in one of the countries in the region will lead to noticeable effects in the neighboring countries. Second, the focus on distributional heterogeneity and the education dimension has been limited. This is surprising, considering that differences in skills development, endowments, and performance can have implications for the country's ability to leverage innovation and digitalization for enhanced market performance and sustainability.

In light of this context, the current research aims to explore the innovation-performance-sustainability link in CEE economies between 2017 and 2024. In particular, it aims to investigate whether innovation potential, digitalization, and education contribute to improving environmental performance. The timeframe from 2017 to 2024 is used because it represents an important phase of the development of the dual transition strategy of the European Union (EU) based on examples of policy milestones such as the European Green Deal, the European Climate Law, and the Digital Europe Programme (2021–2027). For this reason, the research period is especially relevant for studying how the relationships between innovation, digitalization, and education impact sustainability. In addition, the selection of CEE economies as the object of analysis is justified due to their experience of development after the socialist period, when there was a rapid integration into European and international production networks coupled with significant structural differences regarding innovation, digitalization, education, and sustainability.

The originality of this research is based on the incorporation of two analytical dimensions. First, this research applies panel data regression models Random Effects (RE), Pooled OLS, Panel-Corrected Standard Errors (PCSE), and Robust Regression (RREG) to analyze direct effects in the synergy between digitalization–innovation–education and environmental sustainability. Second, this research applies structural equation modeling (SEM) with latent variables to assess the overall impact on innovation's performance. From an analytical point of view, the current study is based on a complex panel of indicators that are derived from the European Innovation Scoreboard and include digital and innovation indicators, education-related indicators, and environmental data, in terms of environmental performance, environment-related technologies, and fine particulate air emissions.

The novelty of the paper resides in its contribution to the literature in several important ways. First, it develops an integrated analytical framework that jointly examines innovation capacity, digitalization, education, and environmental sustainability within the specific context of CEE countries. In this way, the study bridges the research gap that exists in the current literature, where these dimensions are commonly considered independently, not as interdependent factors that contribute to sustainable change. Additionally, the article extends the current literature by accounting for direct and total effects using latent variable modeling, which provides a deeper analysis of the links between innovation, digitalization, human resources, and sustainable performance. The article also contributes to the existing body of knowledge on CEE countries, providing insights for policymakers concerning the importance of education, digital readiness, and green innovation for sustainable development.

The remainder of the paper is structured as follows: Section 2 presents the theoretical framework and literature review related to innovation, digitalization, performance, and sustainability. Section 3 discusses the data, variables, and methodological approach. Finally, Section 4 presents the empirical results and direct and overall effects. Section 5 concludes the paper, providing a summary of the main results, as well as policy implications, research limitations, and future research avenues.

Theoretical Framework and Literature Review

The most recent literature increasingly treats technological innovation and digitalization as driving forces of competitiveness and sustainability. However, there is limited conclusive evidence of whether digitalization and innovation drive market performance, employment dynamics, and sustainability simultaneously. This is particularly relevant for CEE, which faces challenges in developing innovation potential, market performance, and sustainability, particularly in a context of uneven development. The literature generally suggests that digitalization and innovation potential affect productivity and sustainability in a conditional and heterogeneous way, but not in an integrated way that is particularly relevant to CEE. It is the unique developmental paths of the CEE countries that make it an important empirical setting for this study. Specifically, they experienced fast economic integration into international and European value chains, despite still holding certain differences concerning their innovativeness, digitalization, educational systems, institutional quality, and environmental management.

At the macro level, digitalization, green innovation, renewable energy, and financial development have been found to enhance environmental sustainability, while European evidence also links digitalization and e-governance to carbon neutrality and broader sustainability progress (Karlilar Pata, Balcilar, and Emir 2023; Wang et al. 2025a). Within the EU, digitalization, innovation, and environmental policy have been shown to reinforce sustainable production, suggesting that technological upgrading may support the ecological transition at the country level (Guaita Martínez et al. 2022; Mircea et al. 2023). The findings of these empirical studies converge to propose the following hypothesis: digital transformation can improve sustainability performance through the development of digital capabilities, organizational flexibility, and strategic alignment; simultaneously,

industrial digitalization can improve environmental performance through the implementation of cleaner production technologies and structural upgrading (Wen, Lee, and Song 2021; Lu, Li, and Yuen 2023).

The findings of other empirical studies propose the following hypotheses: the digital economy can promote green innovation; digital capabilities can foster green collaborative innovation through learning and organizational orientation, thus supporting the argument for the sustainability benefits of innovation and digitalization (Chen et al. 2025; Xie and Wang 2025). The competitiveness dimension of the nexus is equally important for this study. Research on SMEs shows that digitalization can stimulate product and process innovation, although the magnitude of the effect depends on firm characteristics and internal R&D structures (Radicic and Petkovic 2023). AI readiness has also been associated with stronger international performance, suggesting that digital preparedness may improve firms' external competitiveness (Denicolai, Zucchella, and Magnani 2021). More strategic contributions argue that digital servitization, ecosystem orchestration, and Industry 4.0 strengthen value creation, knowledge integration, and capability development, thereby improving the foundations of long-term competitiveness and innovation-based renewal (Kohtamäki et al. 2019; Linde et al. 2021).

This argument is reinforced by work showing that Industry 4.0 functions as a roadmap to sustainable innovation in manufacturing (Ghobakhloo et al. 2021). Review-based studies further support the systemic relevance of digitalization, arguing that digital tools can support the transformation of sustainable business models and broader "digital sustainability," although only under appropriate organizational and strategic conditions (Guandalini 2022; Broccardo et al. 2023). Reviews focused on the SDGs, circular economy, and SMEs similarly suggest that digital technologies can contribute to a sustainable transition, but only when combined with governance quality, implementation capacity, and organizational readiness (Castro, Fernández, and Colsa 2021; Chauhan, Parida, and Dhir 2022). Related work suggests that organizational culture affects the link between sustainability and digitalization in small and medium-sized enterprises (SMEs), which supports the idea that the results of innovation activities are contingent on factors beyond the simple use of technology (Isensee et al. 2020).

To add to the narrative overview and provide a more structured overview of the field, Figure 1 presents a VOSviewer keyword co-occurrence map, which has been generated on the basis of articles in the Web of Science database with the Topic query "digitalization AND innovation AND sustainability".

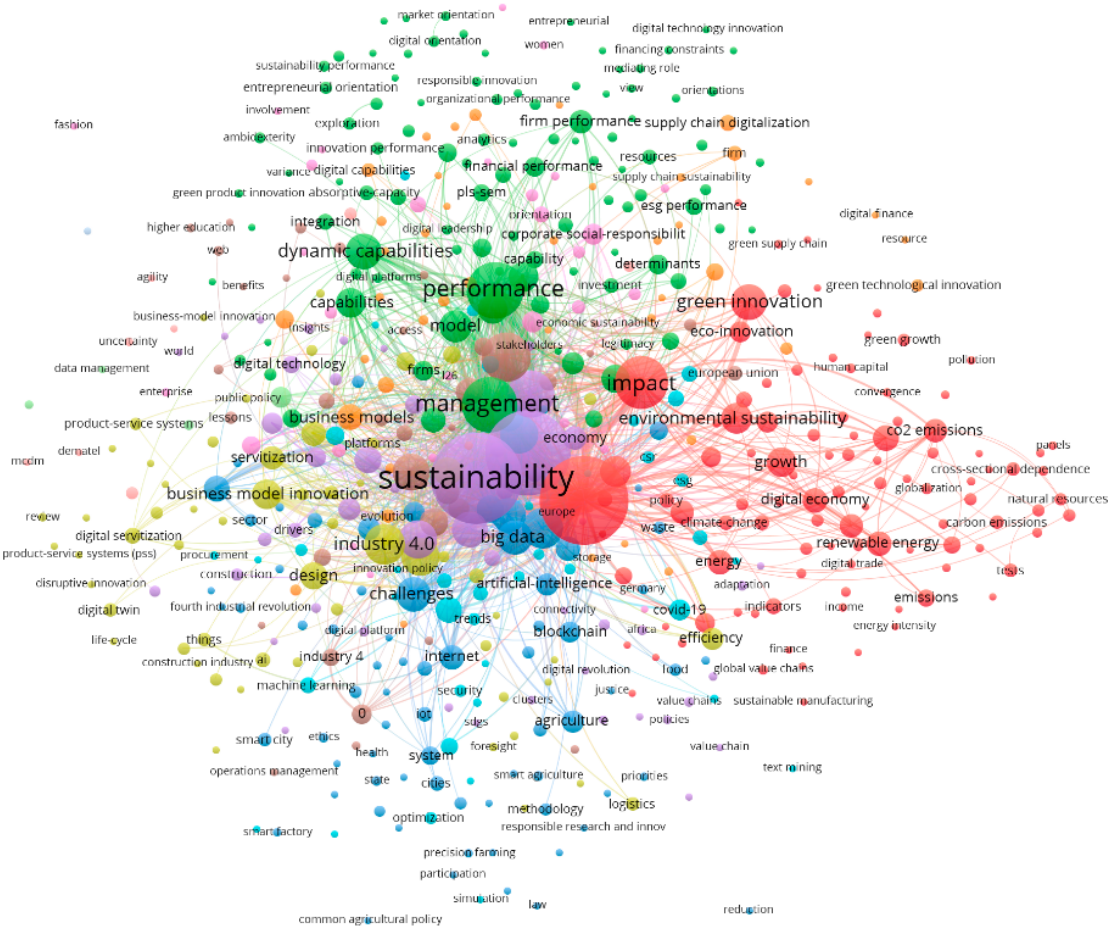


Figure 1. Keyword co-occurrence map of the literature on digitalization, innovation, and sustainability based on Web of Science records
Source: authors' elaboration in VOSviewer.

Beyond its descriptive role, the bibliometric map helps position the research within the broader literature and clarifies the contribution of the analysis. As shown in Figure 1 below, the existing literature focuses predominantly on a highly integrated set of topics related to sustainability, performance, the digital economy, green innovation, and growth. At the same time, the diagram reinforces the point that the academic discourse in this area is relatively disjointed, given that many scholars have written papers focusing on one or two aspects of the relationships between the three variables. This fact is particularly pertinent to this study, which attempts to integrate all these variables. While previous research has explored the connections between digitalization, innovation, and sustainability from an environmental, management, or competitive perspective, little effort has been made to determine how these interact with performance, employment, interdependencies, and regional differences. Thus, the bibliometric analysis supports the rationale of the research by showing both the growing importance of the topic and the need for a more integrated analytical framework.

For CEE countries, one of the key findings in the literature is that the effects of innovation and digitalization are not homogeneous. Quantile-based analysis has found that the effects of digitalization, green investment, and financial development on sustainability are not uniform, and the effects tend to be more pronounced in countries with more advanced complementary

capabilities (Hung 2023; Wang et al. 2025b). Similarly, heterogeneous effects have been found in studies demonstrating that digitalization may increase emissions unless counteracted by green technological innovation or the use of renewable energy, suggesting that technological upgrade is effective only in certain structural conditions (Li et al. 2025; Rani et al. 2025). Country- and context-specific studies have found that digital infrastructure can have a synergistic effect on coordination, productivity, and sustainability, but these effects are highly contingent upon the structural and contextual conditions (Moshood et al. 2024; Manu and Asongu 2025).

Nonetheless, the literature maintains its fragmented focus on the innovation–performance–sustainability triad, with some research focusing on sustainability outcomes, others on green innovation and competitiveness, and the majority using non-spatial methods (Denicolai, Zucchella, and Magnani 2021; Chen et al. 2025). This is particularly limiting for CEE countries, where geographic proximity, trade, education differences, and EU policy spillovers are highly relevant, especially considering that the current literature does not test the capacity of innovation and digitalization in one country to enhance the market performance and sustainability of neighboring countries (Guaita Martínez et al. 2022; Wang et al. 2025a).

Data and Methodology

Data and Indicators Used in the Empirical Analysis

The empirical analysis is based on a country-level panel dataset provided by the European Innovation Scoreboard (EIS). The dataset covers ten Central and Eastern European countries: Bulgaria, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia, analyzed over the period 2017 to 2024. The period from 2017 to 2024 was selected because it represents an important stage at which the EU's dual-transition strategy gradually became more established through initiatives such as the European Green Deal, the European Climate Law, and the Digital Europe Programme (2021–2027). It also enabled a systematic cross-country analysis based on recently published EIS data.

The EIS is designed to provide a harmonized and methodologically comparable framework for cross-country and cross-temporal analysis of innovation performance. In line with the proposed structural equation modeling (SEM), the indicators are grouped into three analytical domains: environmental sustainability, digital and innovation, and education-related indicators. The selection of these indicators is justified by their relevance to the key variables of the conceptual model of the study, namely linking environmental sustainability performance and pressures for pollution reduction with digital and innovative capacities, as well as with the education and knowledge inputs which enable the diffusion and adoption of sustainable innovations. These measures are based on the assumption that sustainable development and innovation performance are determined by the effects of ecological, technological, and human capital.

A list of the indicators employed in the empirical analysis and extracted from the EIS for the period 2017–2024 is presented below.

Environmental Sustainability Indicators:

- *Environmental Sustainability (ENV_SUS)*: Reflects the environmental performance dimension associated with national innovation systems and captures the extent to which countries combine innovation development with sustainability-oriented outcomes.
- *Environment-related Technologies (ENV_TECH)*: Measures the development and diffusion of environment-related technologies and reflects the capacity of the economy to generate technological solutions addressing environmental challenges and green transition objectives.
- *Emissions of Fine Particulates (PM25)*: Captures the level of emissions of fine particulate matter generated in economic activity and is used as an indicator of environmental pressure and pollution intensity. Lower values are associated with better environmental performance and a more sustainable production structure.

Digital and Innovation Indicators:

- *Direct and Indirect Government Support of Business R&D (GOV_RD)*: Measures the public support provided to business research and development through direct funding and indirect fiscal instruments. It reflects the institutional commitment to stimulating private-sector innovation activity.
- *Employed ICT Specialists (ICT_EMP)*: Indicates the share of ICT specialists in total employment and captures the availability of advanced digital human resources required for technology adoption, digital transformation, and innovation diffusion.
- *Individuals with Above Basic Overall Digital Skills (DIG_SKL)*: Reflects the proportion of the population possessing advanced digital competences, thus capturing the general digital readiness of society and its capacity to engage with knowledge-intensive and technology-driven activities.
- *Innovation Expenditures per Person Employed (INN_EXP)*: Measures the level of innovation-related expenditures relative to employment and serves as a proxy for firm-level and economy-level commitment to innovation investment.
- *Knowledge-intensive Services Exports (KIS_EXP)*: *Captures* the export performance of knowledge-intensive services and reflects the international competitiveness of economies in sectors characterized by high value added, knowledge content, and innovation intensity.
- *PCT Patent Applications (PCT_PAT)*: Measures the number of patent applications filed under the Patent Cooperation Treaty and is employed as an indicator of technological output, inventive activity, and internationally relevant innovation capacity.

Education-Related Indicators:

- *Population Involved in Lifelong Learning (LLL)*: Measures the participation of the adult population in education and training activities and reflects the degree to which countries support the continuous upgrading of skills and competences over the life course.

- *Population with Tertiary Education (TER_EDU)*: Captures the share of the population having completed tertiary education and serves as a core indicator of advanced human capital formation and knowledge potential.
- *International Co-authored Articles (CO_AUT)*: Reflects the extent of international academic collaboration through co-authored research articles and is used as an indicator of research openness, academic connectivity, and knowledge integration into global networks.
- *Job-to-job Mobility of HRST (HRST_MOB)*: Measures the mobility of human resources in science and technology across jobs and sectors and captures the circulation of highly skilled labor, which contributes to knowledge diffusion and innovation spillovers.
- *Intellectual Assets (INT_AST)*: Reflects the creation of codified knowledge assets and innovation-related intangible outputs, such as patents, trademarks, or designs, and captures the extent to which knowledge generation is transformed into formalized intellectual property.

Although the indicators are grouped under three major analytical categories, it is apparent that their role is complementary rather than segmented. The environmental sustainability indicators encompass ecological success and the green nature of national development paths. The digital and innovation indicators embrace inputs and outputs of technology-based competitiveness, including support from the public sector, digital workforces, innovation spending, and patenting. Education-related indicators provide an understanding of the human and knowledge base of national innovation success over time, with a focus on formal education, lifelong learning, academic collaboration, and the creation of intellectual property.

The data provided offer an integrated empirical basis for investigating relationships between sustainability, digitalization, innovation, and education in selected CEE countries. The combination of environmental, technological, and human factors into the panel data model allows the capture of country-level and time-related aspects between 2017 and 2024. This approach is especially important for investigating the evolution of new European innovation systems and the drivers behind sustainable and knowledge-intensive growth.

Table 1. Descriptive statistics

Variables	Mean	Std. Dev.	Min	Max	Skew.	Kurt.
PM25	79.041	25.708	25.6	115.9	– .537	2.141
DIG	82.523	18.473	43.8	121.5	– .008	2.94
GOV RD	56.073	54.709	2.7	223.9	1.088	3.326
ICT EMP	90.225	29.347	38.7	171	.784	4.126
EMP IMP	68.516	34.789	10.3	151.2	.293	2.404
ICT TRN	66.831	41.435	0	152.2	.357	2.325
ENV SUS	77.95	17.505	32.9	109.9	– .323	2.695
ENV TECH	94.965	38.229	0	188.7	.261	3.077

Variables	Mean	Std. Dev.	Min	Max	Skew.	Kurt.
MHT EXP	78.404	27.699	35.6	118	– .024	1.41
FIN SUP	65.859	25.867	23.6	118.8	.026	1.98
FIRM INV	64.472	25.067	15	122.4	– .132	2.302
HR	74.078	33.44	18.3	151.8	.138	2.087
DIG SKL	71.386	29.613	16.6	140.2	– .621	2.928
INN EXP	44.875	24.442	2.7	119.9	.194	2.89
INT AST	63.998	21.253	27.6	116.7	.426	2.605
CO AUT	89.343	59.874	18.6	239.8	.991	2.932
HRST MOB	96.76	69.005	0	267.6	.698	2.946
KIS EXP	53.356	15.594	13.7	87.7	– .414	3.19
PCT PAT	45.802	14.807	19.2	94.6	.855	4.028
LLL	87.708	59.221	4.2	226.4	.732	2.468
TER EDU	88.575	50.856	0	200.6	.39	3.178
RES PROD	55.365	30.105	2.9	110.2	– .149	1.868
SAL IMP	68.831	16.7	39.3	101.7	.155	1.934
SII	71.814	20.97	35.5	118.2	.128	2.349

Source: authors' elaboration in Stata 16.

Table 1 indicates significant variation across the variables, evidencing significant cross-country and intertemporal heterogeneity within the selected sample. The highest variations are observed for the HRST_MOB, CO_AUT, LLL, GOV_RD, and TER_EDU variables. These findings imply significant differences for human capital mobility, academic collaboration, lifelong learning, government support for business research and development, and educational attainment at the tertiary level among the ten countries. In contrast, variables such as KIS_EXP, PCT_PAT, ENV_SUS, and DIG appear to have relatively smaller variations, as indicated by their standard deviations. The descriptive statistics for the variables suggest that the dataset is sufficiently heterogeneous for comparative panel analysis and statistically well-behaved for subsequent econometric analysis.

To support the descriptive statistics provided above and to better visualize the dynamics of the countries considered, Figures 2–4 illustrate the panel evolution of the main indicators grouped by the three analytical dimensions considered in this study: environmental sustainability, digitalization/innovation, and education.

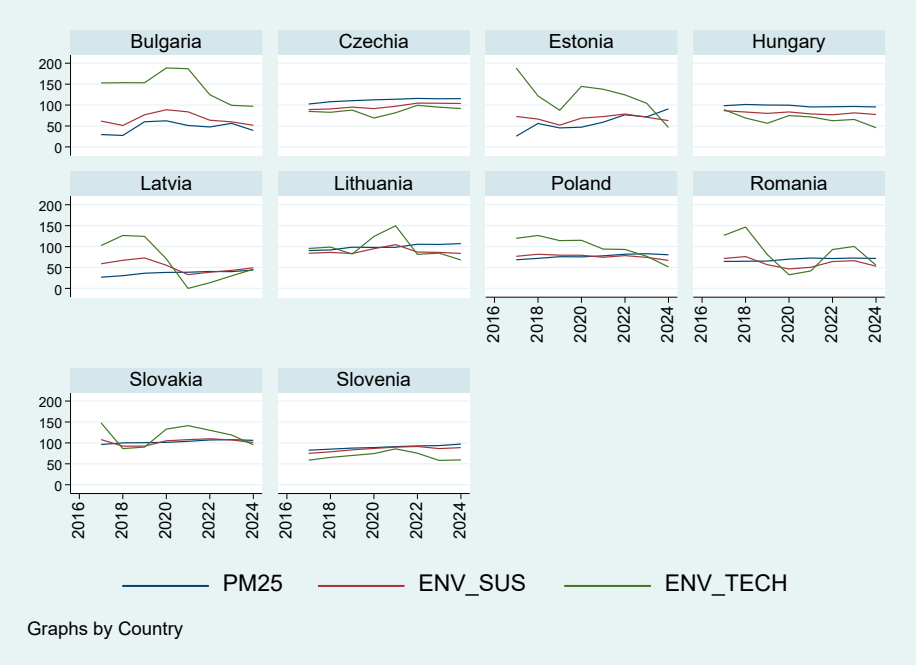


Figure 2. Panel evolution of environmental sustainability indicators
Source: authors' elaboration in Stata 16.

Figure 2 indicates that the environmental sustainability indicators vary somewhat unevenly across countries over the period. While PM25 and ENV_SUS appear to be relatively stable in some cases, ENV_TECH fluctuates more significantly, suggesting large variations in the dynamics of green technologies.

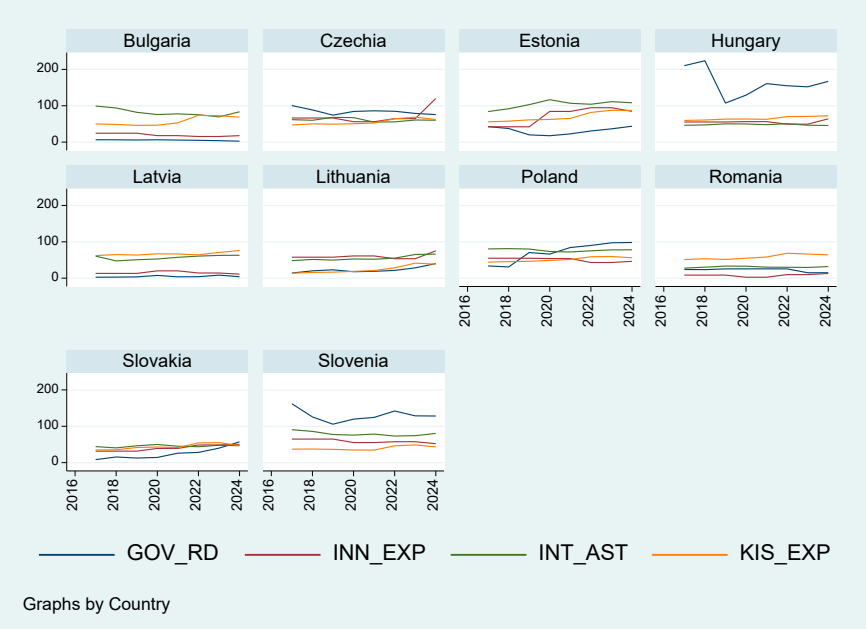


Figure 3. Panel evolution of digitalization and innovation indicators
Source: authors' elaboration in Stata 16.

Figure 3 indicates that the digitalization and innovation indicators vary somewhat heterogeneously across countries, with noticeable variations in terms of both level and dynamics. For instance,

GOV_RD and INT_AST differ more significantly across countries, while INN_EXP and KIS_EXP vary somewhat more smoothly.

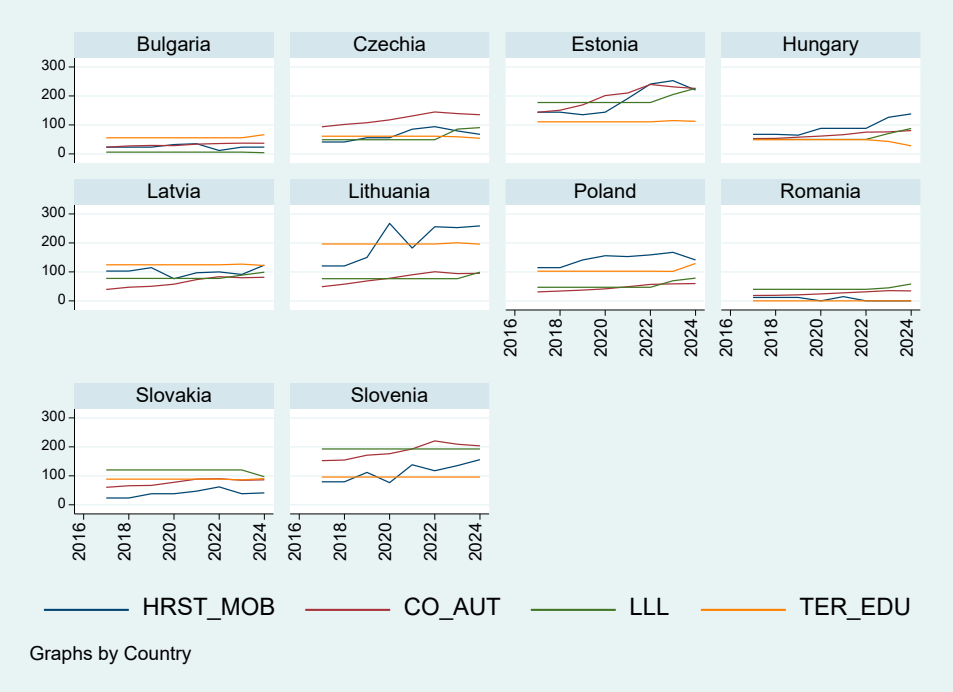


Figure 4. Panel evolution of education indicators
Source: authors' elaboration in Stata 16.

Figure 4 indicates that there is an evident upward trend in education-related indicators, especially HRST_MOB, CO_AUT, and LLL over time, although with varying degrees of change across countries. At the same time, Figure 4 also confirms that there are large variations in human capital and knowledge performance across the countries included in the panel sample.

Methodology

To examine the determinants of the variables across countries and over time, the empirical analysis is based on a complex set of modern econometric techniques, embedding correlation analysis, panel data regression models, and structural equation modeling (SEM).

To obtain a preliminary understanding of the relationships between the variables included in the analysis, a correlation analysis was first conducted. This method identifies the direction and strength of linear relationships between variables and provides an initial indication of possible associations among the studied indicators. At the same time, correlation analysis serves as a diagnostic step for identifying potential multicollinearity issues that may influence the estimation of econometric models (Porter and Gujarati 2009).

Moreover, several panel data regression model specifications were developed and estimated through several alternative strategies. The main specification is based on a Random Effects model that is estimated via a Generalized Least Squares method. In this model specification, the effects that are specific to a country are treated as randomly distributed and independent

of the other independent variables. Baltagi (2021) describes this model in detail. Random effects were chosen based on several methodological aspects.

First, in contrast to the fixed effects approach, it considers variability within and between countries, potentially yielding more efficient estimates. In addition, the random-effects estimator preserves degrees of freedom in relatively small panel samples and allows the inclusion of time-invariant characteristics that can help explain cross-country differences. Furthermore, by treating sampled countries as representative of a broader population, the random-effects framework supports more generalizable inference. The alternative model specification that was developed and estimated is an Ordinary Least Squares model that is based on a pooling procedure and Driscoll-Kraay standard errors. The Driscoll-Kraay procedure adjusts the covariance matrix in such a way that the standard errors that are obtained remain consistent in the presence of such forms of dependence. Driscoll and Kraay (1998) describe this procedure in detail.

In addition to these model specifications and estimators, the analysis also employs a Panel-Corrected Standard Errors procedure. The PCSE procedure adjusts the estimated covariance matrix so that the resulting standard errors remain reliable. The procedure does not affect the coefficient estimates, as detailed by Beck and Katz (1995).

Finally, to mitigate the effects of extreme values and possible violations of classical regression analysis assumptions, this study also incorporates robust regression analysis (RREG) estimations. The robust regression analysis reduces the impact of influential observations, thus limiting the effects of possible outliers on the estimated parameters. In this way, the estimated parameters remain stable even when the distribution of residuals differs from the assumptions of classical regression analysis (Huber 1981; Rousseeuw and Leroy 1987).

Aside from these econometric analyses, this study also employed a Structural Equation Modeling (SEM) approach in order to examine the structural relationships between the primary dimensions of analysis. The SEM approach allows for the simultaneous estimation of relationships between multiple observed variables, including latent variables that represent broader theoretical constructs (Bollen 1989; Kline 2016). This is particularly useful when multiple underlying processes are present simultaneously, where some variables are not directly measurable. One of the principal benefits of using SEM is the ability to combine measurement models with structural paths in a single type of analytical structure. This allows for the evaluation of the validity of the constructs as well as the strength of the relationships that exist between the constructs. This is essentially a more holistic approach to the conceptual model on which the analysis is based.

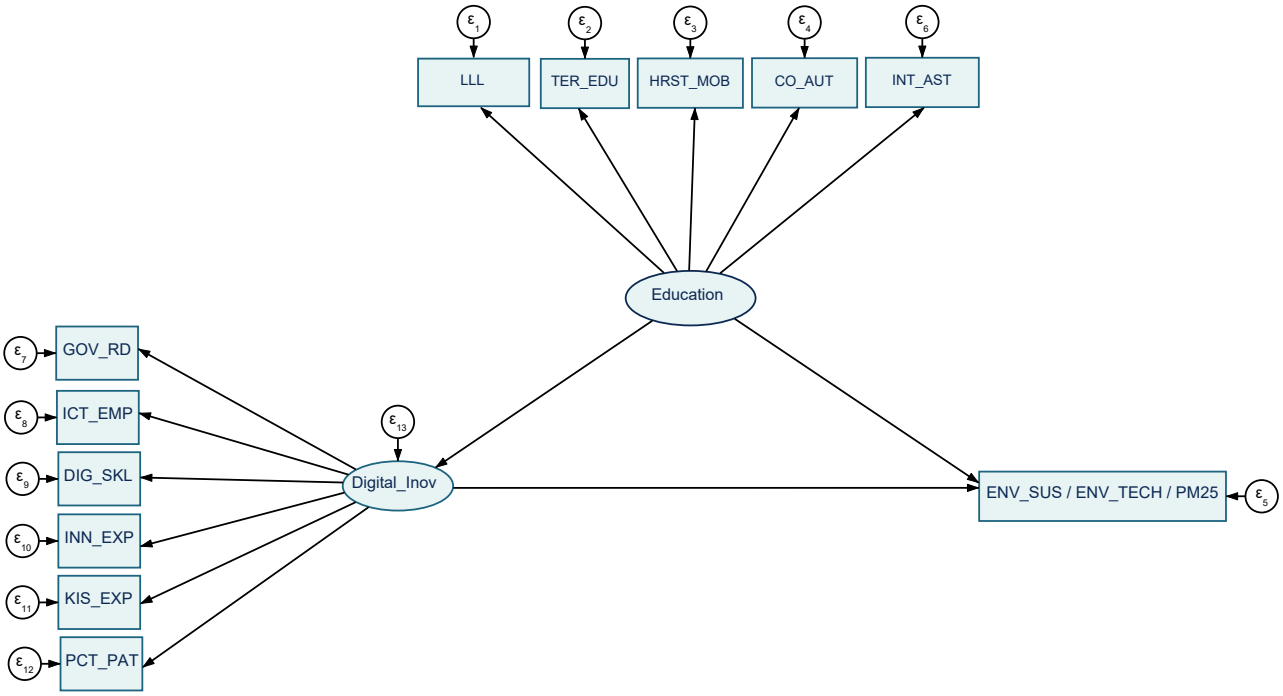


Figure 5. General configuration of the SEM model
Source: authors' elaboration in Stata 16.

As can be seen in Figure 5 above, the SEM model comprises three key dimensions of analysis. The first is the first latent construct Digital_Inov, which is measured by several indicators that represent different aspects of technological capacity and innovation: GOV_RD, ICT_EMP, DIG_SKL, INN_EXP, KIS_EXP, and PCT_PAT. These indicators collectively represent the general dynamics of digital development. The second construct is Education, which is measured by the indicators LLL, TER_EDU, HRST_MOB, CO_AUT, and INT_AST. These indicators represent different aspects of the education system, thereby reflecting its multidimensionality. The environmental dimension is based on the indicators ENV_SUS, ENV_TECH, and PM25.

Overall, the incorporation of these approaches provides a more comprehensive framework for analyzing these relationships.

The research hypotheses are:

- *H1: Digitalization, innovation, and education positively influence environmental performance sustainability in CEE countries;*
- *H2: Digitalization, innovation, and education positively influence environment-related technologies in CEE countries;*
- *H3: Digitalization, innovation, and education positively influence the reduction of emissions by fine particulates in CEE countries.*

Results and Discussion

Correlation Analysis

The pairwise correlations between the variables included in the analysis are reported in Table 2 and Figure 6, providing an initial overview of the relationships linking environmental sustainability, digitalization, innovation, and education indicators. Examining these associations identifies preliminary patterns before proceeding to more complex econometric modeling.

Table 2. Pairwise correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
(1) ENV_SUS	1.000													
(2) ENV_TECH	0.349	1.000												
(3) PM25	0.787	−0.213	1.000											
(4) GOV_RD	0.303	−0.376	0.514	1.000										
(5) ICT_EMP	0.140	0.090	0.040	0.102	1.000									
(6) DIG_SKL	0.295	−0.201	0.326	0.249	0.665	1.000								
(7) INN_EXP	0.522	−0.031	0.575	0.453	0.632	0.729	1.000							
(8) INT_AST	−0.149	0.207	−0.296	−0.002	0.728	0.266	0.442	1.000						
(9) CO_AUT	0.223	−0.136	0.241	0.288	0.813	0.589	0.673	0.569	1.000					
(10) HRST_MOB	0.081	−0.086	0.127	0.095	0.511	0.631	0.577	0.453	0.512	1.000				
(11) KIS_EXP	−0.460	−0.194	−0.341	0.036	0.185	0.037	−0.106	0.155	0.094	−0.080	1.000			
(12) PCT_PAT	0.142	−0.210	0.145	0.618	0.594	0.446	0.540	0.493	0.691	0.292	−0.012	1.000		
(13) LLL	0.155	−0.138	0.128	0.192	0.716	0.550	0.482	0.428	0.862	0.451	−0.045	0.650	1.000	
(14) TER_EDU	0.134	0.012	0.033	−0.216	0.367	0.531	0.340	0.299	0.264	0.742	−0.455	0.156	0.336	1.000

Source: authors' elaboration in Stata 16.

As shown in Table 2, several moderate to strong correlations emerge across the analyzed variables.

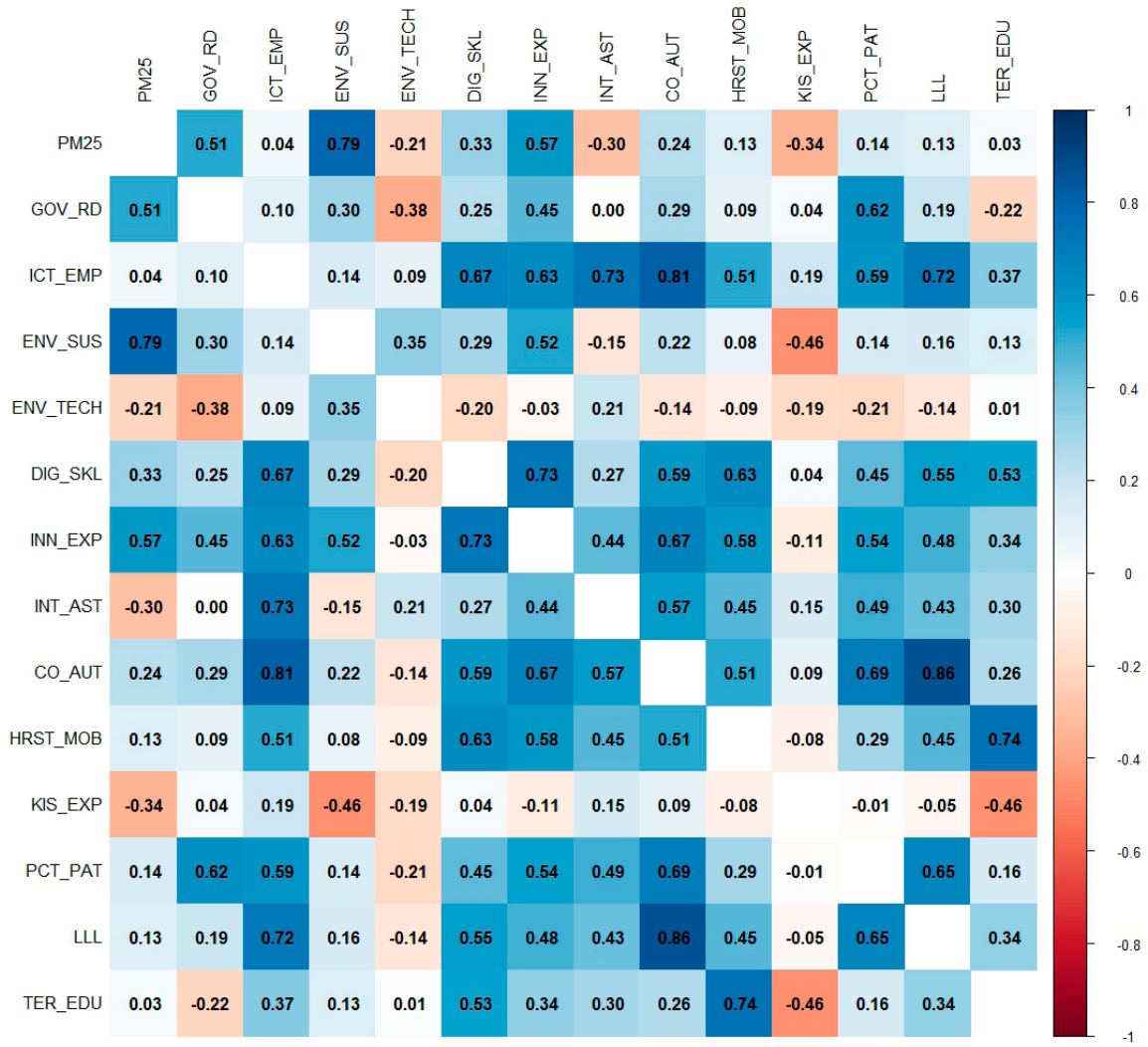


Figure 6. Heatmap of correlation coefficients for all variables
Source: authors' elaboration in RStudio.

A complementary perspective is offered by the multidimensional representation shown in Figure 7, which depicts the dual-layer relationships between the digital, educational, innovation, and sustainability indicators.

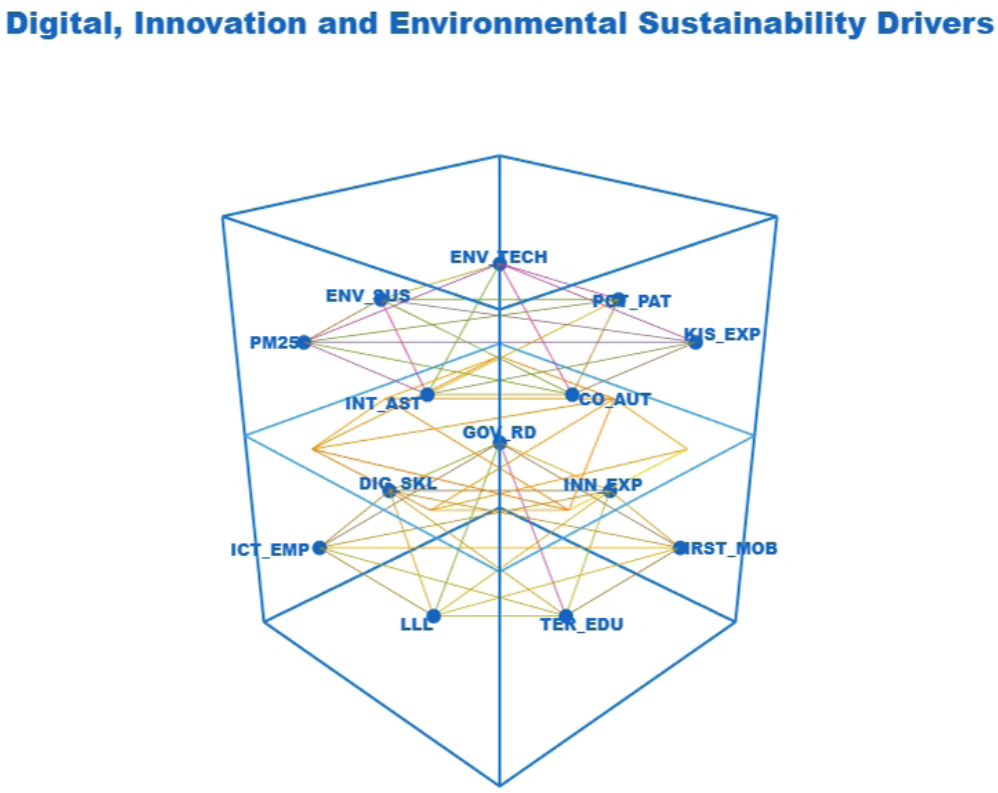


Figure 7. Multidimensional links (dual-layer cube) between digital, innovation, education and sustainability indicators
Source: authors' elaboration in RStudio.

Figure 7 illustrates the simultaneous interaction among all dimensions, which highlights the importance of knowledge-based factors like digital literacy, research cooperation, and spending on innovation within the larger context of the system. Before proceeding to the econometric estimations, potential multicollinearity among the explanatory variables was assessed using the Variance Inflation Factor (VIF) and the corresponding tolerance values. The results indicate that CO_AUT records the highest VIF value of 8.79, followed by TER_EDU and ICT_EMP, both with VIF values of 7.51, respectively. DIG_SKL presents a VIF of 6.00, while LLL and INN_EXP show VIF values of 5.93 and 5.63. Slightly lower values are observed for HRST_MOB (VIF = 5.39) and PCT_PAT (VIF = 5.31). The remaining variables display more moderate levels, with INT_AST recording a VIF of 4.32, GOV_RD a VIF of 4.13, and KIS_EXP the lowest VIF value of 3.08. Overall, the mean VIF is 5.78, indicating moderate levels of multicollinearity within the model, while all tolerance values remain above the commonly accepted threshold, suggesting that multicollinearity does not pose a critical concern for the subsequent econometric estimations.

Results of the Panel Data Modeling

To estimate the direct impact of the dimensions of digitalization, innovation, and education on the three coordinates representing the dependent variables, namely environmental performance oriented towards innovation and sustainability (ENV_SUS), the development and diffusion of environment-related technologies (ENV_TECH), and the level of emissions of fine particulate matter generated in economic activity (PM25), we have applied four panel regression specifications,

namely Random Effects (RE), Pooled OLS, Panel-Corrected Standard Errors (PCSE), and Robust Regression (RREG).

The results estimated for the environmental performance oriented towards innovation and sustainability (ENV_SUS) are presented in Table 3. The share of ICT specialists in total employment (ICT_EMP) and the level of innovation-related expenditures relative to employment (INN_EXP) had a positive and statistically significant influence on environmental performance oriented towards innovation and sustainability (ENV_SUS), with the effect being more pronounced in the case of innovation-related expenditures per employee (INN_EXP). In contrast, intellectual assets (INT_AST) and the export performance of knowledge-intensive services (KIS_EXP) had a negative and statistically significant influence on this dimension (ENV_SUS). These findings are similar to those obtained by Wen, Lee, and Song (2021), Lu, Li, and Yuen (2023), Chen et al. (2025), and Xie and Wang (2025), who revealed that digital capabilities can improve environmental performance through green collaborative innovation through learning and organizational orientation.

Therefore, the first hypothesis (H1), which proposed that digitalization, innovation, and education positively influence environmental performance sustainability in CEE countries, is supported only for the share of ICT specialists in total employment and the innovation expenditures per person employed.

Table 3. Results of the panel regression models (dependent variable: ENV_SUS)

	(1)	(2)	(3)	(4)
	ENV_SUS	ENV_SUS	ENV_SUS	ENV_SUS
	RE	Pooled OLS	PCSE	RREG
GOV_RD	0.0 633 (0.0 467)	0.0 633 (0.0 551)	0.0 633 (0.0 347)	0.0 608 (0.0 517)
ICT_EMP	0.301* (0.117)	0.301 (0.180)	0.301** (0.107)	0.261* (0.130)
DIG_SKL	− 0.111 (0.104)	− 0.111 (0.148)	− 0.111 (0.0 981)	− 0.0 889 (0.115)
INN_EXP	0.459*** (0.122)	0.459** (0.127)	0.459*** (0.0 991)	0.427** (0.135)
INT_AST	− 0.407*** (0.123)	− 0.407** (0.0 961)	− 0.407*** (0.0 960)	− 0.386** (0.136)
CO_AUT	0.0 518 (0.0 622)	0.0 518 (0.0 724)	0.0 518 (0.0 399)	0.0 676 (0.0 688)
HRST_MOB	− 0.0 596 (0.0 423)	− 0.0 596 (0.0 373)	− 0.0 596 (0.0 488)	− 0.0 491 (0.0 468)
KIS_EXP	− 0.489*** (0.141)	− 0.489** (0.0 921)	− 0.489*** (0.136)	− 0.508** (0.156)
PCT_PAT	− 0.321 (0.195)	− 0.321 (0.246)	− 0.321 (0.167)	− 0.319 (0.216)

	(1)	(2)	(3)	(4)
	ENV_SUS	ENV_SUS	ENV_SUS	ENV_SUS
	RE	Pooled OLS	PCSE	RREG
LLL	− 0.0 417 (0.0 516)	− 0.0 417 (0.0 314)	− 0.0 417 (0.0 398)	− 0.0 518 (0.0 572)
TER_EDU	0.0 137 (0.0 677)	0.0 137 (0.0 603)	0.0 137 (0.0 642)	0.00 209 (0.0 749)
_cons	105.0*** (9.133)	105.0*** (5.820)	105.0*** (8.496)	107.6*** (10.11)
N	80	80	80	80
R^2	0.8 567	0.650	0.650	0.592

Note: Standard errors are in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: authors' elaboration in Stata 16.

Regarding the development and diffusion of environment-related technologies (ENV_TECH), the results in Table 4 show a direct and statistically significant positive impact only from the share of ICT specialists in total employment (ICT_EMP). In the CEE region, environment-related technologies (ENV_TECH) were negatively and statistically significantly influenced by the public support provided to business R&D through direct funding and indirect fiscal instruments (GOV_RD), international co-authored articles (CO_AUT), the export performance of knowledge-intensive services (KIS_EXP), and the population with tertiary education (TER_EDU).

From an economic perspective, these results suggest that improvements in these areas are not automatically reflected in stronger environmental technological performance across the region. Although these findings may seem unexpected, they can be explained by several structural features unique to CEE economies. For GOV_RD, the negative coefficient may indicate that public support for R&D is still directed mainly towards general innovation or competitiveness objectives, without a strong focus on green technologies. Similarly, the expansion of knowledge-intensive service exports (KIS_EXP) does not necessarily imply a stronger environmental orientation, as many of these activities may be concentrated in business, financial, or IT services with only indirect links to sustainability outcomes.

The negative relationship identified for tertiary education (TER_EDU) and international academic collaboration (CO_AUT) should also be interpreted carefully. A larger share of tertiary educated population or a higher level of academic cooperation does not automatically translate into environmental innovation if research activities and educational specializations are not sufficiently connected to green sectors. This result may also reflect the persistence of skilled labor migration in several CEE countries, where highly educated individuals contribute increasingly to innovation systems abroad rather than to domestic environmental technological development (Noja et al. 2018).

Thus, the second hypothesis (H2), which proposed that digitalization, innovation, and education positively influence environment-related technologies in CEE countries, is only partially supported, specifically for the share of ICT specialists in total employment.

Table 4. Results of the panel regression models (dependent variable: ENV_TECH)

	(1)	(2)	(3)	(4)
	ENV_TECH	ENV_TECH	ENV_TECH	ENV_TECH
	RE	Pooled OLS	PCSE	RREG
GOV_RD	−0.324* (0.126)	−0.324** (0.0718)	−0.324*** (0.0970)	−0.324* (0.136)
ICT_EMP	1.037** (0.317)	1.037 (0.488)	1.037** (0.388)	0.901* (0.342)
DIG_SKL	−0.391 (0.281)	−0.391 (0.519)	−0.391 (0.326)	−0.452 (0.303)
INN_EXP	0.438 (0.330)	0.438 (0.604)	0.438 (0.330)	0.561 (0.355)
INT_AST	0.121 (0.332)	0.121 (0.240)	0.121 (0.283)	0.151 (0.358)
CO_AUT	−0.374* (0.168)	−0.374 (0.207)	−0.374** (0.128)	−0.343 (0.181)
HRST_MOB	0.146 (0.114)	0.146 (0.129)	0.146 (0.0986)	0.138 (0.123)
KIS_EXP	−1.182** (0.382)	−1.182* (0.461)	−1.182** (0.436)	−1.111** (0.412)
PCT_PAT	0.0225 (0.529)	0.0225 (0.401)	0.0225 (0.430)	−0.0762 (0.570)
LLL	−0.0417 (0.140)	−0.0417 (0.0757)	−0.0417 (0.0821)	−0.0224 (0.151)
TER_EDU	−0.432* (0.183)	−0.432 (0.220)	−0.432** (0.167)	−0.435* (0.197)
_cons	143.4*** (24.71)	143.4** (32.10)	143.4*** (25.07)	149.3*** (26.63)
N	80	80	80	80
R^2	0.9317	0.463	0.463	0.422

Note: Standard errors in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: authors' elaboration in Stata 16.

The empirical results for emissions of fine particulate matter generated in economic activity (PM25) are reported in Table 5. Favorable influences (as indicated by the negative coefficients obtained, which reflect a decrease in the level of fine particulate matter emissions generated) that are statistically

significant were observed for the following variables: the proportion of the population possessing advanced digital competences (DIG_SKL), the export performance of knowledge-intensive services (KIS_EXP), patent applications filed under the Patent Cooperation Treaty (PCT) (PCT_PAT) and intellectual assets (INT_AST). Thus, a higher proportion of the population with advanced digital skills, intellectual assets, more patent applications, and a higher level of exports of knowledge-based services reduces emissions of fine particles. This may be explained by the fact that digitalization optimizes processes in SMEs (Chen et al. 2025; Xie and Wang 2025) and facilitates the adoption of more energy-efficient and pollution-reducing technologies, as smart technologies help reduce pollution (Marcu et al. 2016; Drăcea et al. 2026).

In contrast, direct and indirect government support of business R&D (GOV_RD), the share of ICT specialists in total employment (ICT_EMP), the level of innovation-related expenditures relative to employment (INN_EXP), and international co-authored articles (CO_AUT) are associated with an increase in PM25 emissions generated in economic activity, as indicated by the positive and statistically significant coefficients obtained. These results may reflect the structure of CEE economies, where industrialization and technological development may initially have environmental costs, with positive environmental effects emerging only after a longer time horizon (Lazăr, Minea, and Purcel 2016).

Table 5. Results of the panel regression models (dependent variable: PM25)

	(1)	(2)	(3)	(4)
	PM25	PM25	PM25	PM25
	RE	Pooled OLS	PCSE	RREG
GOV_RD	0.199*** (0.0474)	0.199** (0.0562)	0.199*** (0.0433)	0.200*** (0.0482)
ICT_EMP	0.250* (0.119)	0.250 (0.159)	0.250* (0.103)	0.370** (0.121)
DIG_SKL	−0.215* (0.106)	−0.215*** (0.0353)	−0.215** (0.0779)	−0.187 (0.107)
INN_EXP	0.740*** (0.124)	0.740** (0.154)	0.740*** (0.116)	0.654*** (0.126)
INT_AST	−0.786*** (0.125)	−0.786*** (0.0863)	−0.786*** (0.0941)	−0.807*** (0.127)
CO_AUT	0.166** (0.0632)	0.166** (0.0342)	0.166*** (0.0470)	0.139* (0.0642)
HRST_MOB	−0.0455 (0.0429)	−0.0455 (0.0270)	−0.0455 (0.0454)	−0.0267 (0.0436)
KIS_EXP	−0.392** (0.144)	−0.392* (0.157)	−0.392** (0.125)	−0.482** (0.146)
PCT_PAT	−0.669*** (0.199)	−0.669* (0.200)	−0.669*** (0.185)	−0.655** (0.202)

	(1)	(2)	(3)	(4)
	PM25	PM25	PM25	PM25
	RE	Pooled OLS	PCSE	RREG
LLL	−0.0669 (0.0525)	−0.0669 (0.0383)	−0.0669 (0.0465)	−0.0674 (0.0533)
TER_EDU	0.0499 (0.0688)	0.0499 (0.0786)	0.0499 (0.0506)	0.0126 (0.0699)
_cons	120.3*** (9.279)	120.3*** (8.167)	120.3*** (6.865)	121.1*** (9.430)
N	80	80	80	80
R^2	0.9612	0.8325	0.832	0.823

Note: Standard errors in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: authors' elaboration in Stata 16.

Therefore, the third hypothesis (H3), which proposed that digitalization, innovation, and education help reduce PM25 emissions in CEE countries, is partially supported, specifically for the proportion of the population with advanced digital skills, the export performance of knowledge-intensive services, patent applications, and intellectual assets.

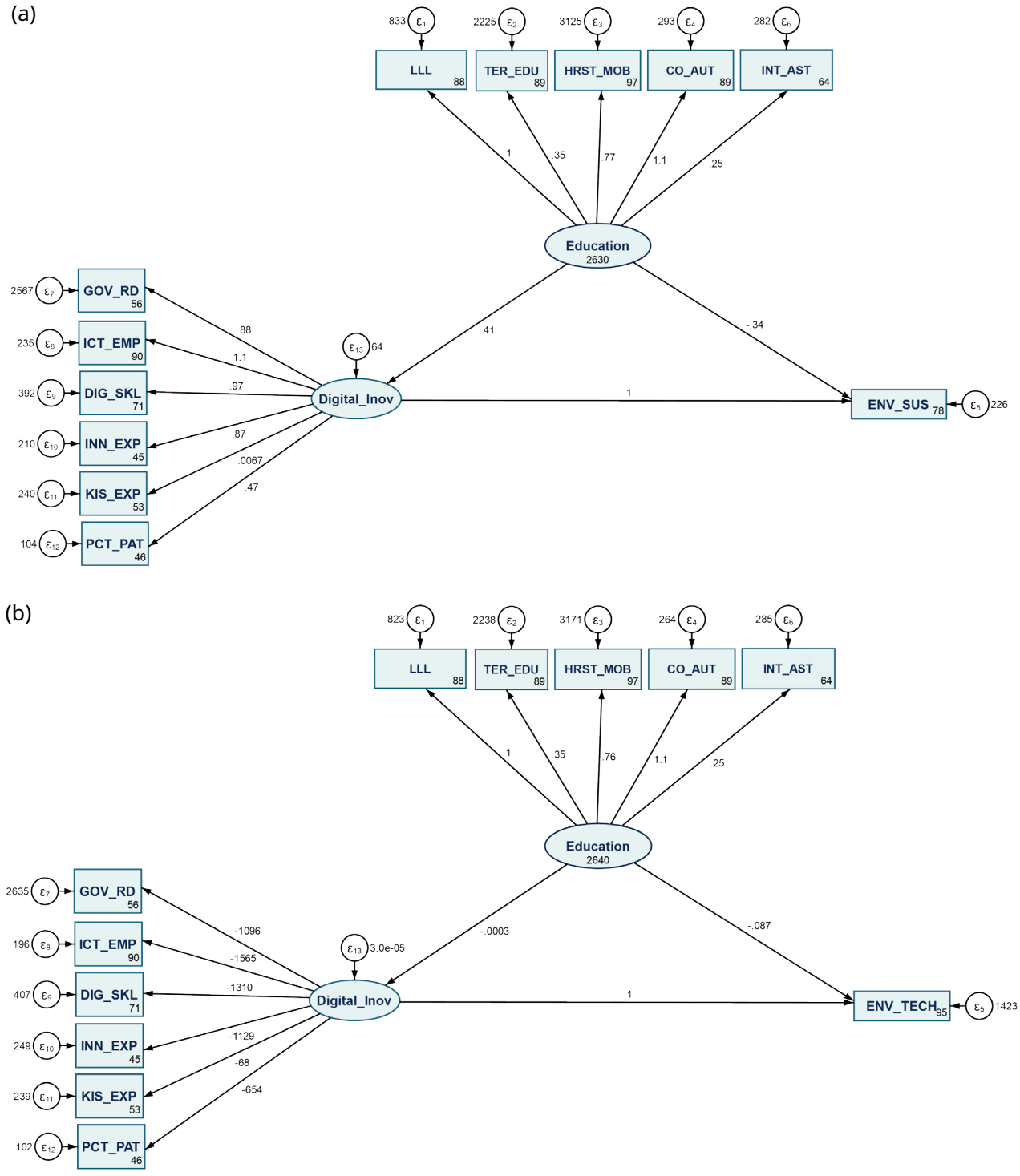
Results of Structural Equations Models (SEM)

To further examine the relationships between the key dimensions identified in the previous analyses, a Structural Equation Modeling (SEM) framework using the Maximum Likelihood Estimator (MLE) was applied. This approach allows for the simultaneous assessment of the measurement relationships between the latent constructs and their observed indicators, as well as the structural links between the latent variables and the environmental outcomes. The main results for each dependent variable are presented in Figure 8.

The digital and innovation dimensions gathered within the latent variable (Digital_Inov) generated positive effects on sustainable environmental performance (ENV_SUS) (Figure 8(a)), as well as on environment-related technologies (ENV_TECH) (Figure 8(b)), mediated by the indirect impact of favorable influences from education (Education). However, the construct of education (Education) negatively influences both sustainable environmental performance (ENV_SUS) (Figure 8(a)) and environment-related technologies (ENV_TECH) (Figure 8(b)), although this arises from the positive influences of its subdimensions. The constructs of digitalization and innovation (Digital_Inov) encompass positive effects from all the sub-dimensions introduced in the case of environmental performance (ENV_SUS), while in the case of environment-related technologies (ENV_TECH), these effects are negative. Therefore, a higher share of the population with advanced digitalization and innovation skills (Digital_Inov), together with stronger education features, contributes to higher environmental performance (ENV_SUS). This can be explained by the role of digitalization and innovation in improving SME efficiency and supporting the adoption of cleaner, more energy-efficient technologies, including smart solutions

that help reduce pollution (Marcu et al. 2016; Chen et al. 2025; Xie and Wang 2025; Drăcea et al. 2026).

Therefore, hypotheses H1 (which proposed that digitalization, innovation, and education positively influence environmental performance sustainability in CEE countries) and H2 (which proposed that digitalization, innovation, and education favorably influence environment-related technologies in CEE countries) are partially supported only in the case of digitalization and innovation, while education needs some reconsideration in the CEE countries.



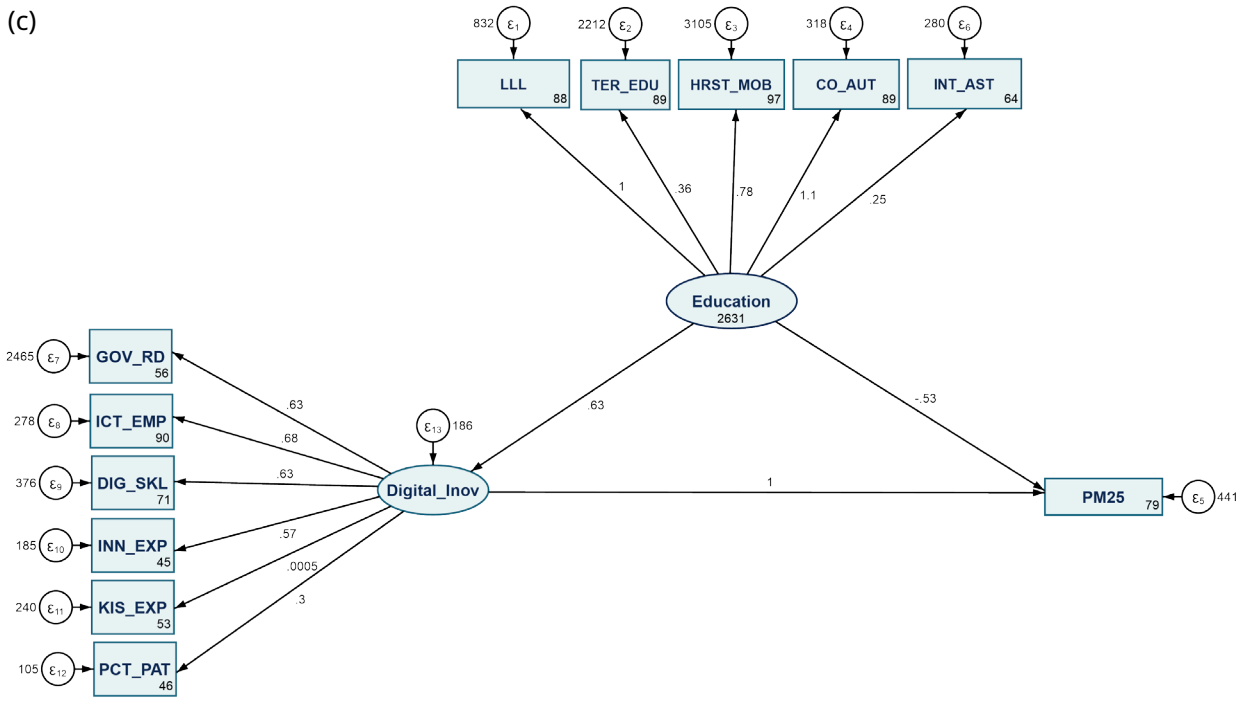


Figure 8. Results of structural equations models (SEM), on sustainable environmental performance (ENV_SUS) (a), environment-related technologies (ENV_TECH) (b), and PM25 emissions (c)
Source: authors' elaboration in Stata 16.

Regarding the implications for pollution, we observe that digitalization and innovation lead to increased PM25 emissions (Figure 8(c)), acting as a mediating factor for education, which enhances digitalization and innovation. However, the construct of education (Education) favorably influenced emissions of fine particulates (PM25) by reducing them. Thus, H3 (which posits that digitalization, innovation, and education help reduce PM25 emissions in CEE countries) is supported only for education, while digitalization and innovation require adaptation to reduce pollution.

Conclusion

This paper explored the relationships between innovation, digitalization, education, and the environment in CEE countries from 2017 to 2024. In particular, the environmental dimension was represented by environmental sustainability, environment-related technology, and fine particulate matter (PM2.5) emissions. Methodologically, the paper relied on a range of panel data regressions, including a random effects model, pooled ordinary least squares (OLS) estimates with Driscoll-Kraay standard errors, panel-corrected standard errors (PCSE), and robust regression. The paper also examined the general relationship between innovation, education, and the environment through the lens of structural equation modeling (SEM).

The main results indicated that the dimensions of digitalization and innovation, proxied by the share of ICT specialists in total employment and the innovation expenditures per person employed, positively and directly influenced environmental performance sustainability in CEE countries (H1) and environment-related technologies (H2). Meanwhile, PM25 emissions were reduced by digitalization and innovation, proxied by individuals with advanced digital skills, the export performance

of knowledge-intensive services, and patent applications, as well as by education, proxied by intellectual assets (H3). Overall, the SEM findings revealed that digitalization and innovation act as a beneficial motor for the environment, while education needs to be aligned with green technology. Based on these results, these areas should be further supported and intensified.

Regarding the negative effects obtained, the following measures should be considered:

- Reorienting public support for R&D by introducing dedicated funding programs for green innovation and prioritizing projects towards renewable energy, circular economy, energy efficiency, and pollution reduction technologies;
- Orienting knowledge-intensive services towards the green sector;
- Capitalizing on intellectual assets, education, and research towards green technologies;
- Reducing the brain drain in CEE countries;
- Integrating innovation with pollution reduction objectives;
- Supporting the development of competencies for green and digital transformation by introducing new curriculum reforms and promoting lifelong learning;
- Fostering cooperation between universities, businesses, and government bodies;
- Adjusting higher education and vocational education programs to meet the needs of green technologies, circular economy projects, and digital innovations.

The implementation of these policies is likely to boost the ability of CEE countries to adopt sustainable technologies, address skills gaps, and transform human capital into a competitive advantage for green growth.

The study has several limitations that should be acknowledged. First, it is constrained by the availability and comparability of data across CEE countries. Even though European databases provide a high degree of harmonization, some indicators might still have national peculiarities, and some dimensions of green innovation might be only indirectly accounted for using proxies. Second, there is a risk of a time lag the effects of innovations, digitalization, and R&D on environmental performance are often delayed. Therefore, due to the relatively limited time horizon of our analysis, the full impact of these factors on the environment might not be captured. Additionally, endogeneity issues cannot be totally ruled out because there can be a two-way relationship between innovation and environmental performance, and other omitted factors may have influenced the analysis. Lastly, the limited time period precludes a proper analysis of the structural transformation pathways in CEE economies. Further studies could improve our understanding of the issue by using more extended time series and even firm- or regional-level data. Furthermore, it would be beneficial to consider more developed EU economies when conducting a comparative analysis and employing a spatial econometric framework.

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