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**Energy Price Volatility and Digital Capability in Shaping FDI Location Decisions:
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Abstract

This study examines how energy price volatility and business analytics capability jointly shape foreign direct investment (FDI) location decisions in Central and Eastern Europe in the post-pandemic era. Using a balanced panel of forty countries from 2010 to 2025, the analysis employs a unified dynamic system-GMM framework complemented by a formal panel threshold model and machine-learning validation. The results indicate that energy price volatility does not uniformly deter FDI; instead, its impact operates through conditional and regime-dependent mechanisms. While the direct effect of volatility is limited once dynamic persistence is controlled for, its interaction with digital adoption is statistically significant, implying that digitally advanced economies internalise energy risk more transparently into capital allocation decisions. The threshold analysis identifies a critical level of digital adoption above which the sensitivity of FDI to energy volatility changes structurally. Machine-learning validation confirms the dominant predictive role of energy risk and digital capability under non-parametric modelling. The findings highlight digital infrastructure as a strategic resilience mechanism and provide policy-relevant insights for sustaining FDI inflows under persistent energy uncertainty.

Keywords: Energy Price Volatility, Digital Adoption, Foreign Direct Investment, Threshold Effects, Post-Pandemic Adjustment

1. Introduction

Foreign direct investment (FDI) location decisions have become increasingly sensitive to risk-based cost structures in the post-pandemic global economy. Among the emerging risk channels, energy price volatility has assumed heightened importance due to geopolitical tensions, supply-chain disruptions, and structural energy transitions across Europe. For Central and Eastern Europe (CEE), a region characterised by energy import dependence, export-oriented manufacturing, and deep integration within the European Union, volatility in energy markets directly affects production costs, profit expectations, and multinational firms' location choices (Barteková & Ziesemer, 2019; Marangoz, 2025; Saussay & Sato, 2024). Empirical evidence indicates that unstable energy prices undermine investment predictability, increase operational risk, and reduce host-country attractiveness, particularly in energy-intensive sectors (Min, 2022; Pavlík et al., 2025). In parallel, rapid advances in digital technologies and business analytics have transformed firms' capacity to process information, forecast costs, and manage macroeconomic uncertainty (Pham et al., 2024; Qamruzzaman, 2026). Yet, despite these structural shifts, the interaction between energy price volatility and digital capability remains underexplored in the FDI literature.

The broader empirical literature identifies market size, institutional quality, macroeconomic stability, and trade openness as key determinants of FDI (Abdi et al., 2024; Abu Bakar et al., 2022; Gupta et al., 2023; Wang et al., 2022). A growing strand further shows that macroeconomic

instability—including inflation, exchange-rate volatility, and energy price shocks—discourages foreign investment inflows (Adebayo et al., 2021; Ayinde et al., 2024; Ben-Obi et al., 2025; Elumalue et al., 2025). Within Europe, higher electricity and energy prices have been found to deter inward FDI, particularly under volatile or weakly regulated energy regimes (Barteková & Ziesemer, 2019; Doğan et al., 2020; Saussay & Sato, 2024). Meanwhile, technological advancement, renewable energy adoption, and institutional strength can mitigate adverse investment effects by improving cost stability and sustainability (Dimnwobi et al., 2022; Khan et al., 2022; Pham et al., 2024).

However, three important gaps remain. First, most studies focus on energy price levels rather than volatility as a forward-looking risk factor that shapes investment uncertainty. Second, digital adoption and business analytics capability, despite their growing relevance in risk management, have rarely been modelled as conditioning mechanisms in the energy–FDI nexus. Third, existing analyses often rely on linear specifications that do not explicitly test whether the impact of energy volatility varies across different levels of digital readiness or institutional strength. These gaps are particularly consequential in the post-COVID environment, where firms increasingly prioritise resilience, data-driven risk assessment, and adaptive location strategies (Fazaaloh, 2024; Imran & Rashid, 2023; Rathnayaka Mudiyansele et al., 2021).

This study addresses these gaps by examining whether business analytics capability moderates the impact of energy price volatility on FDI location decisions in Central and Eastern Europe during the period 2010–2025. Conceptually, the paper integrates energy risk and digital capability within a unified investment-location framework grounded in Dunning’s Eclectic (OLI) Paradigm, Transaction Cost Economics, Institutional Theory, and the Resource-Based View. Energy price volatility is treated as a location-specific risk factor that erodes cost predictability, while digital adoption, proxied by the Digital Adoption Index, is conceptualised as a strategic capability that enhances information processing, lowers transaction costs, and strengthens investment resilience.

Empirically, the analysis is structured around a dynamic panel identification strategy using system-GMM estimation to account for persistence and endogeneity in FDI inflows. To test for nonlinear moderation effects, the study employs a panel threshold framework that endogenously identifies whether the impact of energy price volatility differs across regimes of digital readiness. This unified empirical approach allows the paper to examine both dynamic adjustment and regime-dependent investment behaviour within a coherent econometric structure. Additional robustness checks, including alternative volatility constructions and machine-learning-based predictive validation, are implemented to confirm the stability of the core findings without departing from the primary identification logic.

The study contributes to the Financial Innovation literature in three ways. First, it reconceptualises energy price volatility as a financial risk channel influencing international capital allocation. Second, it identifies digital capability as a resilience mechanism that conditions risk transmission into investment decisions. Third, it provides post-pandemic evidence from a strategically

important European region where energy security, digital transformation, and FDI competitiveness intersect.

Guided by this framework, the study addresses the following research questions:

(RQ1) How does energy price volatility affect FDI location decisions in Central and Eastern Europe?

(RQ2) What is the direct effect of business analytics capability, proxied by the Digital Adoption Index, on FDI location decisions?

(RQ3) Does business analytics capability moderate the relationship between energy price volatility and FDI location decisions?

(RQ4) How do labour costs, institutional quality, inflation, exchange-rate volatility, trade openness, renewable energy share, post-COVID conditions, and EU membership jointly influence FDI location decisions in Central and Eastern Europe?

By integrating risk volatility, digital resilience, and dynamic investment behaviour within a coherent empirical framework, this study offers policy-relevant insights into how CEE economies can sustain FDI inflows amid persistent energy uncertainty.

2. Literature Review

This section reviews the extant literature relevant to the study by examining the underlying theoretical perspectives, synthesising empirical evidence, and developing the research hypotheses that guide the analysis.

2.1 Theoretical Literature Review

The theoretical literature provides the conceptual foundation for understanding how energy price volatility, digital capability, and structural conditions influence foreign direct investment location decisions. This study draws on four complementary theoretical perspectives, including Dunning's Eclectic (OLI) Paradigm, Transaction Cost Economics, Institutional Theory, and the Resource-Based View, to explain the mechanisms through which host-country characteristics and firm capabilities jointly shape international investment behaviour.

2.1.1 Eclectic (OLI) Paradigm Theory

Dunning's Eclectic Paradigm asserts that foreign direct investment decisions are influenced by the interplay of ownership (O), location (L), and internalisation (I) benefits (Dunning, 1988). In this context, the characteristics of the host country's location, including cost factors, institutional stability, energy availability, and market accessibility, significantly influence the investment

decisions of multinational enterprises (MNEs). Fluctuations in energy prices diminish locational benefits by heightening production uncertainty and operational expenses, especially in energy-import-reliant countries like those in Central and Eastern Europe (Barteková & Ziesemer, 2019; Saussay & Sato, 2024). In contrast, digital adoption and analytical capabilities augment internalisation advantages by allowing enterprises to optimise supply chains, predict costs, and handle cross-border risks more effectively (Pham et al., 2024; Qamruzzaman, 2026). The OLI paradigm offers a robust theoretical framework for analysing the direct impacts of energy price volatility and digital adoption on foreign direct investment location choices, as well as their interaction.

2.1.2 Transaction Cost Economics (TCE)

Transaction Cost Economics elucidates corporate conduct within uncertainty by highlighting cost minimisation due to knowledge asymmetries, market volatility, and contractual incompleteness (Coase, 1937; Williamson, 1985). From a Transaction Cost Economics perspective, fluctuating energy prices elevate transaction and coordination expenses by complicating long-term contracts, pricing strategies, and investment planning, thereby deterring foreign direct investment inflows (Min, 2022; Marangoz, 2025). Advanced business analytics diminish transaction costs by enhancing information processing, forecasting precision, and adaptive decision-making, hence mitigating the negative impacts of volatility (Ayinde et al., 2024; Imran & Rashid, 2023). This theoretical framework posits that digital adoption mitigates the adverse effects of energy price volatility on foreign direct investment, especially in post-pandemic contexts marked by increased uncertainty.

2.1.3 Institutional Theory

Institutional Theory argues that economic outcomes are shaped by formal and informal rules, regulatory quality, and governance effectiveness (North, 1990). Strong institutions reduce uncertainty, protect property rights, and enhance policy credibility, thereby fostering a stable investment climate conducive to FDI (Antonietti & Mondolo, 2023; Goswami, 2023; Gupta et al., 2023). In the context of energy markets, effective regulation and institutional quality can cushion firms against price shocks and macroeconomic instability (Elumalue et al., 2025; Nyeadi et al., 2022). Moreover, EU membership and post-COVID policy coordination further reinforce institutional convergence within CEE countries, influencing investment attractiveness (Fazaalloh, 2024; Rathnayaka Mudiyanse et al., 2021). Institutional Theory, therefore, underpins the inclusion of regulatory quality, EU membership, and post-pandemic dynamics as critical control factors shaping FDI location decisions.

2.1.4 Resource-Based View (RBV)

The Resource-Based View conceptualises competitive advantage as stemming from valuable, rare, inimitable, and non-substitutable firm resources (Barney, 1991). At the macro level, host-country digital infrastructure and analytics capability can be interpreted as strategic location-specific

resources that attract efficiency-seeking FDI. Digital adoption enhances firms' ability to leverage data, manage energy risks, and integrate renewable energy solutions, thereby improving resilience to volatility (Dimnwobi et al., 2022; Khan et al., 2022; Pham et al., 2024). Countries with higher digital readiness thus provide MNEs with superior resource environments, reinforcing FDI inflows even amid adverse energy price dynamics. RBV therefore supports the argument that digital adoption not only directly attracts FDI but also strengthens resilience against energy-related shocks.

2.2 Empirical Literature Review and Hypothesis Development

Empirical studies on FDI location determinants consistently emphasise market size, institutional quality, cost conditions, and macroeconomic stability. Abdi et al. (2024) examined the drivers of FDI inflows in Africa using panel regression techniques and found that institutional quality and trade openness significantly promote FDI, while macroeconomic instability undermines inflows. Similarly, Abu Bakar et al. (2022), through a systematic literature review, concluded that cost structures, regulatory environments, and technological readiness are decisive in FDI location selection. Focusing on macroeconomic volatility, Adebayo et al. (2021) showed that exchange-rate and inflation volatility exert destabilising effects on FDI, a finding reinforced by Elumalue et al. (2025) and Ben-Obi et al. (2025), who emphasise the role of uncertainty and volatility channels in shaping investment decisions. Within Europe, Barteková and Ziesemer (2019) demonstrated, using EU panel data, that higher electricity prices significantly deter inward FDI, while Saussay and Sato (2024), using firm-level global data, confirmed that energy price shocks influence industrial investment location decisions. Collectively, these findings suggest that unstable energy and macroeconomic environments weaken location advantages and increase investment risk. Accordingly, the first hypothesis is proposed:

H1: Energy price volatility has a negative and significant effect on FDI location decisions in Central and Eastern Europe.

A growing strand of empirical research highlights the role of digital capability, innovation, and structural transformation in shaping FDI dynamics. Pham et al. (2024), analysing 60 countries using panel econometric techniques, found that innovation and renewable energy adoption jointly enhance FDI inflows. Qamruzzaman (2026) reported that technological advancement and trade openness improve FDI sustainability outcomes. Studies focusing on institutional and technological complementarities, such as Antonietti and Mondolo (2023) and Goswami (2023), show that stronger institutional and technological frameworks amplify FDI attractiveness. These results align with the Resource-Based View (Barney, 1991) and the OLI paradigm (Dunning, 1988), which posit that host-country capabilities and location-specific advantages attract efficiency-seeking FDI. In this context, digital adoption—capturing analytics readiness and technological penetration—represents a strategic capability that enhances investor confidence and operational efficiency. This motivates the second hypothesis:

H2: Business analytics capability, proxied by the Digital Adoption Index, has a positive and significant effect on FDI location decisions in Central and Eastern Europe.

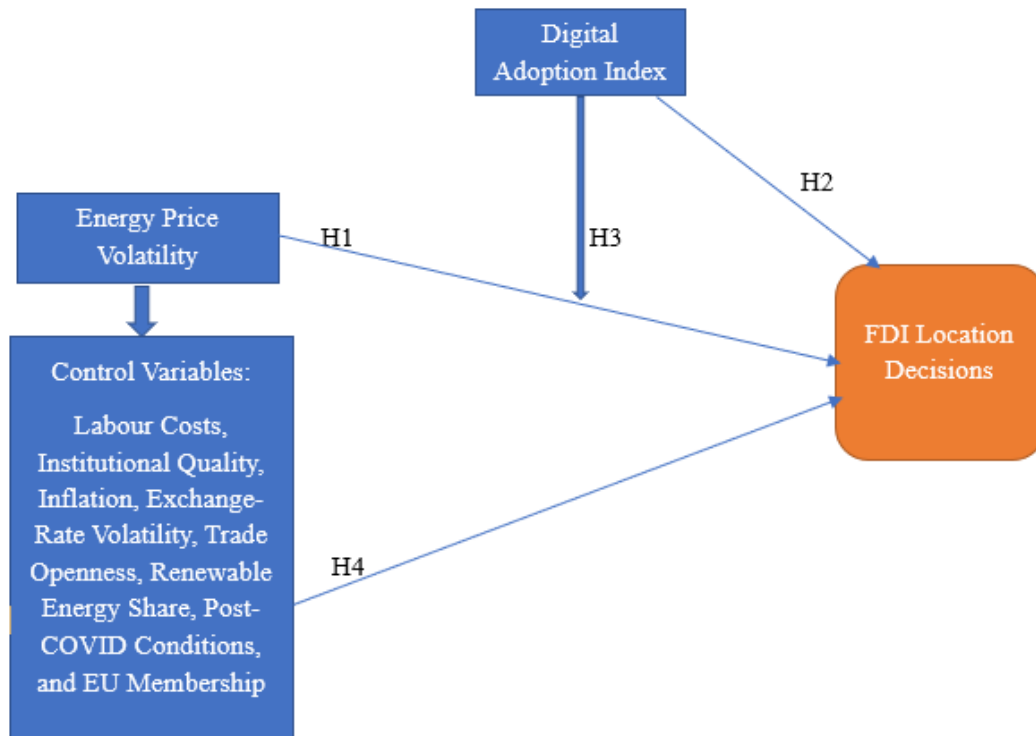
Beyond direct effects, recent studies emphasise interaction-based and regime-dependent mechanisms in FDI behaviour. Ayinde et al. (2024) show that crisis conditions amplify the sensitivity of FDI to macroeconomic shocks, while Min (2022) and Marangoz (2025) document that energy volatility transmits through cost and inflation channels, affecting investment decisions during periods of geopolitical and supply-chain stress. However, empirical work integrating digital capability as a moderating factor in the energy–FDI nexus remains limited. Drawing on Transaction Cost Economics (Coase, 1937; Williamson, 1985) and the Resource-Based View, digital adoption is expected to reduce informational frictions, enhance forecasting accuracy, and improve firms’ ability to process and price risk. Consequently, digital capability may condition the extent to which energy price volatility translates into investment deterrence. This theoretical and empirical gap motivates the third hypothesis:

H3: Business analytics capability moderates the relationship between energy price volatility and FDI location decisions, such that the adverse effect of energy price volatility varies across levels of digital adoption.

Finally, extensive empirical evidence confirms that FDI decisions are jointly influenced by broader macroeconomic and structural factors. Labour costs (Abu Bakar et al., 2022), institutional quality (Gupta et al., 2023; Nyeadi et al., 2022), inflation and exchange-rate volatility (Adebayo et al., 2021; Elumalue et al., 2025), trade openness (Rathnayaka Mudiyansele et al., 2021; Abdi et al., 2024), renewable energy integration (Dimnwobi et al., 2022; Pavlík et al., 2025), post-pandemic conditions (Ayinde et al., 2024), and EU membership effects (Barteková & Ziesemer, 2019) significantly shape host-country attractiveness. Institutional Theory suggests that these structural features define the broader investment climate within which firms evaluate location decisions. Accordingly, the final hypothesis is proposed:

H4: Labour costs, institutional quality, inflation, exchange-rate volatility, trade openness, renewable energy share, post-COVID conditions, and EU membership jointly and significantly influence FDI location decisions in Central and Eastern Europe.

Figure 1: Conceptual Framework of Energy Price Volatility, Digital Adoption, and FDI Location Decisions in Central and Eastern Europe



Source: Author (2026)

Figure 1 presents the theoretical structure underlying the empirical analysis. Energy price volatility is modelled as the primary risk channel influencing foreign direct investment (FDI) location decisions (H1). Consistent with the OLI paradigm and Transaction Cost Economics, unstable energy costs weaken location advantages by increasing operational uncertainty and transaction costs.

The Digital Adoption Index plays a dual role. First, it directly influences FDI location decisions (H2) by enhancing analytics capability, information processing efficiency, and strategic decision-making capacity. Second, it moderates the relationship between energy price volatility and FDI (H3). This moderating pathway reflects the idea that digital capability conditions how energy-related risk is internalised into capital allocation decisions. Rather than eliminating energy risk, higher digital readiness alters its transmission and pricing.

Control variables, including labour costs, institutional quality, inflation, exchange-rate volatility, trade openness, renewable energy share, post-COVID conditions, and EU membership, capture broader structural and macroeconomic determinants of FDI (H4). These factors define the institutional and cost environment within which firms evaluate investment decisions.

Overall, the framework emphasises conditional risk transmission: energy price volatility affects FDI directly, but its magnitude and manifestation depend on host-country digital capability. This conceptual structure directly corresponds to the dynamic moderation and threshold-based empirical strategy employed in the study.

3. Data and Empirical Strategy

3.1 Research Design, Data Sources, and Sample Structure

This study adopts a quantitative longitudinal research design based on a balanced panel framework to examine how energy price volatility and business analytics capability jointly influence foreign direct investment (FDI) location decisions in Central and Eastern Europe (CEE). A panel structure is particularly appropriate because it captures both cross-country heterogeneity and intertemporal dynamics while controlling for unobserved country-specific effects that may bias purely cross-sectional estimations (Wang et al., 2022; Imran & Rashid, 2023).

The sample consists of 40 CEE countries observed annually from 2010 to 2025, yielding 640 country-year observations. The balanced panel enhances comparability across countries and strengthens the efficiency of dynamic estimators.

FDI location decisions are proxied by FDI inflows as a percentage of GDP, obtained from UNCTAD and the World Bank. Energy price volatility (EPV) is constructed from the World Bank energy import price index using the standard deviation of logarithmic returns, consistent with volatility-based investment literature (Min, 2022; Pavlík et al., 2025). Business analytics capability is proxied by the Digital Adoption Index (DAI), scaled between 0 and 1.

Control variables include labour cost index (Eurostat), regulatory quality (Worldwide Governance Indicators), inflation, exchange-rate volatility, trade openness, renewable energy share, EU membership dummy, and a post-COVID dummy (2021–2025), selected based on established FDI and macroeconomic evidence (Abdi et al., 2024; Abu Bakar et al., 2022; Ayinde et al., 2024; Gupta et al., 2023).

3.2 Identification Strategy and Dynamic Panel Specification

FDI inflows exhibit persistence and potential endogeneity due to reverse causality and omitted variable bias. To address these concerns, the study employs a dynamic panel system-GMM estimator. This approach controls for:

- Endogeneity of regressors
- Country-specific unobserved heterogeneity
- Dynamic adjustment in FDI

The baseline specification is:

$$FDI_{it} = \alpha FDI_{i,t-1} + \beta_1 EPV_{it} + \beta_2 DAI_{it} + \beta_3 (EPV_{it} \times DAI_{it}) + \gamma X_{it} + \mu_i + \varepsilon_{it}$$

Where:

- FDI_{it} denotes FDI intensity
- EPV_{it} represents energy price volatility
- DAI_{it} captures digital adoption
- $EPV_{it} \times DAI_{it}$ tests moderation
- X_{it} is the vector of control variables
- μ_i denotes country fixed effects

System-GMM uses lagged levels and differences as internal instruments, following best practice in dynamic panel estimation (Ayinde et al., 2024; Wang et al., 2022). Instrument proliferation is controlled using collapsed instrument matrices and lag restrictions.

3.3 Testing for Nonlinear Moderation: Panel Threshold Framework

While the interaction term captures linear moderation, the effect of energy price volatility may vary across distinct regimes of digital readiness. To formally test for regime dependence, the study applies the panel threshold model of Hansen (1999).

The threshold specification is:

$$FDI_{it} = \begin{cases} \alpha_1 + \beta_1 EPV_{it} + \gamma_1 X_{it} + \varepsilon_{it}, & DAI_{it} \leq \tau \\ \alpha_2 + \beta_2 EPV_{it} + \gamma_2 X_{it} + \varepsilon_{it}, & DAI_{it} > \tau \end{cases}$$

Where:

- τ is the endogenously estimated threshold level of digital adoption
- Bootstrap likelihood ratio tests determine threshold significance

This framework allows the data to identify whether energy volatility affects FDI differently in low- and high-digital-capability environments. Unlike arbitrary subgroup analysis, the threshold value is statistically determined, ensuring methodological coherence (Hansen, 1999; Antonietti & Mondolo, 2023).

Importantly, this threshold approach serves as the sole nonlinear testing mechanism in the study, ensuring a unified econometric structure.

3.4 Post-Pandemic Structural Adjustment Within the Dynamic Framework

To assess whether the COVID-19 pandemic structurally altered the energy price volatility–FDI relationship, the post-pandemic effect is incorporated directly into the dynamic system-GMM

framework through interaction terms. Rather than conducting a separate Chow-type break test, which would fragment the identification strategy, structural adjustment is tested within the primary dynamic specification to preserve econometric coherence (Ayinde et al., 2024).

The extended dynamic model is specified as:

$$FDI_{it} = \alpha FDI_{i,t-1} + \beta_1 EPV_{it} + \beta_2 DAI_{it} + \beta_3 (EPV_{it} \times DAI_{it}) \\ + \delta_1 PostCOVID_t + \delta_2 (EPV_{it} \times PostCOVID_t) \\ + \gamma X_{it} + \mu_i + \varepsilon_{it}$$

Where:

- $PostCOVID_t$ is a dummy variable equal to 1 for 2021–2025 and 0 otherwise;
- δ_1 captures the average shift in FDI during the post-pandemic period;
- δ_2 measures whether the sensitivity of FDI to energy price volatility changed after COVID-19.

Interpretation of Structural Parameters

- δ_1 reflects the direct structural impact of the pandemic on FDI inflows, capturing global investment contraction, risk aversion, and supply-chain disruptions.
- δ_2 captures a slope shift in the energy–FDI nexus. A statistically significant coefficient indicates that the marginal effect of energy price volatility on FDI differs in the post-pandemic regime.

The marginal effect of energy price volatility after 2020 becomes:

$$\frac{\partial FDI_{it}}{\partial EPV_{it}} = \beta_1 + \beta_3 DAI_{it} + \delta_2 PostCOVID_t$$

Thus, the pandemic may have:

- Amplified energy-related investment risk (if $\delta_2 < 0$), or
- Reduced sensitivity due to improved risk-management adaptation (if $\delta_2 > 0$).

Identification Rationale

Embedding the structural shift directly into the system-GMM framework ensures:

1. Endogeneity is handled consistently across both pre- and post-pandemic periods.
2. Dynamic persistence in FDI is preserved.
3. Moderation and structural adjustment are jointly evaluated.

4. No parallel model universe is introduced.

This unified approach maintains methodological coherence while allowing the data to determine whether the pandemic represents a regime shift in risk transmission from energy volatility to foreign investment decisions.

3.5 Robustness and Predictive Validation

To ensure that the empirical findings are not sensitive to model specification or measurement choices, a structured robustness strategy is implemented without departing from the primary dynamic system-GMM identification framework.

3.5.1 Alternative Volatility Construction

First, energy price volatility is reconstructed using a conditional volatility approach. Specifically, a GARCH (1,1) model is estimated for the energy import price index, and the conditional variance series is used as an alternative measure of EPV. This allows the analysis to distinguish between unconditional dispersion and time-varying risk, thereby strengthening the financial interpretation of volatility as a forward-looking uncertainty measure (Min, 2022; Pavlík et al., 2025).

3.5.2 Lag Structure Sensitivity

Second, lagged volatility specifications are introduced to account for delayed investment responses. Since FDI location decisions often involve planning horizons and capital adjustment costs, the impact of energy risk may materialise with temporal lags. Including $EPV_{i,t-1}$ ensures that results are not driven solely by contemporaneous effects.

3.5.3 External Instrument Strategy

Third, to further address potential endogeneity, external instruments are employed using global oil price volatility and exogenous gas supply disruption indices. These variables influence domestic energy price volatility but are plausibly exogenous to individual CEE country-level FDI inflows. The inclusion of external instruments strengthens causal interpretation by reinforcing the exclusion restriction within the GMM framework.

3.5.4 Placebo Subsample Test

Fourth, a placebo estimation is conducted on the pre-2019 subsample to verify whether the energy–FDI relationship is structurally different in the post-pandemic era. If the moderation and volatility effects are significantly weaker before 2020, this supports the argument that COVID-19 represents a structural shift rather than a continuation of pre-existing trends.

Predictive Validation via Machine Learning

To complement the econometric results, Random Forest and XGBoost models are estimated strictly for predictive validation. These models do not serve as alternative causal frameworks but

assess whether energy price volatility and digital adoption consistently emerge as dominant predictors under non-parametric, distribution-free modelling.

SHAP (Shapley Additive Explanations) values are used to evaluate feature importance and contribution to prediction outcomes. If EPV and DAI remain top-ranked variables across tree-based ensemble models, this confirms the robustness of the central findings beyond linear functional-form assumptions (Pham et al., 2024).

Importantly, machine-learning models are not used to infer structural parameters or moderation effects; they serve solely to validate predictive relevance and variable ranking consistency.

3.6 Diagnostic Tests and Model Validity

To ensure econometric reliability and internal consistency, a comprehensive set of diagnostic tests is implemented.

3.6.1 Dynamic Panel Validity

For the system-GMM estimations:

- **Arellano–Bond AR (1) and AR (2) tests** evaluate serial correlation in first-differenced residuals. The presence of AR (1) but the absence of AR (2) confirms model consistency.
- **Hansen J-test and Sargan test** assess the validity of overidentifying restrictions. Failure to reject the null supports instrument validity and the appropriateness of internal and external instruments.
- Instrument proliferation is controlled using collapsed instrument matrices and restricted lag depth.

3.6.2 Multicollinearity and Specification

- **Variance Inflation Factors (VIFs)** are computed to ensure no harmful multicollinearity, particularly in the presence of interaction terms.
- The **Hausman test** guides the selection between fixed-effects and random-effects specifications in auxiliary estimations.
- Robust (two-step Windmeijer-corrected) standard errors are employed to correct for heteroskedasticity and finite-sample bias.

3.6.3 Threshold Model Diagnostics

- **Bootstrap likelihood ratio tests** following Hansen (1999) determine whether the estimated digital adoption threshold is statistically significant.

- Confidence intervals for the threshold parameter are constructed using bootstrap replications to ensure reliable regime classification.

Collectively, this robustness and diagnostic framework preserve the unified identification hierarchy of the study:

1. Dynamic system-GMM as the core causal estimator
2. Panel threshold regression is the formal nonlinear extension
3. Structural post-pandemic interaction within the dynamic model
4. Machine-learning models for predictive validation only

This structured approach ensures internal consistency, addresses endogeneity rigorously, formally tests nonlinear moderation, and maintains a coherent econometric architecture aligned with Financial Innovation’s emphasis on financial risk transmission, digital capability, and capital allocation dynamics.

Table 1. Variable Definitions, Measurement, and Data Sources

Variable Category	Variable Name	Symbol	Measurement / Construction	Expected Sign	Data Source
Dependent Variable	Foreign Direct Investment Intensity	FDI	Net FDI inflows as a percentage of GDP (%). Measures relative investment attractiveness and capital allocation intensity.	—	World Bank (WDI)
Core Independent Variable	Energy Price Volatility	EPV	Annual volatility of energy import price index, computed as the standard deviation of logarithmic returns: $EPV_t = \sqrt{\frac{1}{n-1} \sum (\Delta \ln P_t)^2}$. Robustness via GARCH (1,1) conditional volatility.	—	World Bank
Moderating Variable	Business Analytics Capability (Digital Adoption Index)	DAI	Composite index (0–1) capturing digital penetration, technological readiness, and analytics infrastructure. Higher	+	World Bank

Variable Category	Variable Name	Symbol	Measurement / Construction	Expected Sign	Data Source
			values indicate stronger data-driven capacity.		
Interaction Term	Energy Volatility × Digital Capability	EPV×DAI	Multiplicative interaction term capturing moderation effect: $EPV_{it} \times DAI_{it}$.	+	Authors' computation (buffering)
Control Variables	Labour Cost Index	LCI	Index of labour compensation adjusted for productivity. Captures cost-competitiveness effects on FDI.	±	Eurostat
	Institutional Quality (Regulatory Quality)	INST	Regulatory Quality index (−2.5 to +2.5), higher values indicate stronger governance and policy credibility.	+	Worldwide Governance Indicators (WGI)
	Inflation Rate	INF	Annual percentage change in consumer price index (%). Proxy for macroeconomic instability.	−	World Bank
	Exchange Rate Volatility	EXV	Standard deviation of annual log changes in nominal exchange rate: $\sigma(\Delta \ln ER)$.	−	World Bank
	Trade Openness	TO	Sum of exports and imports as percentage of GDP (%). Captures global value chain integration.	+	World Bank
	Renewable Energy Share	REN	Share of renewable energy in total final energy consumption (%). Proxy for energy diversification and transition dynamics.	±	World Bank
	Post-COVID Dummy	PCOV	Dummy variable: 1 = 2021–2025; 0 otherwise. Captures	±	Authors' construction

Variable Category	Variable Name	Symbol	Measurement / Construction	Expected Sign	Data Source
			structural post-pandemic regime shift.		
	EU Membership Dummy	EU	Dummy variable: 1 = EU member; 0 otherwise. Captures institutional harmonisation and policy credibility effects.	+	European Commission

4. Results and Discussion

4.1 Results

Table 2. Descriptive Statistics of Study Variables (2010–2025, N = 640)

Variable	Mean	Std. Deviation	Minimum	Maximum
FDI Intensity (% of GDP)	6.56	36.79	−112.43	289.65
Energy Price Volatility (EPV)	0.07	0.04	0.01	0.22
Digital Adoption Index (DAI)	0.74	0.15	0.31	0.97
Labour Cost Index	136.70	31.69	82.40	231.50
Institutional Quality (INST)	0.64	0.56	−1.02	1.83
Inflation Rate (%)	3.61	5.17	−4.62	24.18
Exchange Rate Volatility (EXV)	0.08	0.14	0.00	0.91
Trade Openness (% of GDP)	109.15	38.11	44.20	204.73
Renewable Energy Share (%)	24.82	15.97	4.10	61.45

Note. Statistics are based on a balanced panel of 40 Central and Eastern European countries observed annually from 2010 to 2025.

The descriptive statistics in Table 2 reveal pronounced cross-country and intertemporal heterogeneity in FDI and its determinants across Central and Eastern Europe during 2010–2025. Average FDI intensity is 6.56 per cent of GDP; however, the exceptionally large standard deviation

and wide range indicate substantial fluctuations in capital inflows, including episodes of extreme surges and contractions. This dispersion reflects the sensitivity of foreign investment to macroeconomic shocks, policy changes, and global uncertainty, consistent with the study's emphasis on risk transmission mechanisms.

Energy price volatility exhibits a moderate but economically meaningful spread, confirming that CEE economies have been persistently exposed to external energy shocks. Given the region's reliance on energy imports, this volatility constitutes a non-trivial cost-risk factor for multinational enterprises. The Digital Adoption Index averages 0.74, suggesting relatively advanced digital infrastructure overall, yet the variation across countries highlights uneven analytics capability and technological readiness. This dispersion is essential for identifying potential regime-dependent effects in the threshold analysis.

Labour costs and trade openness display substantial variation, reflecting structural differences in productivity, wage competitiveness, and integration into global value chains. Institutional quality is positive on average but ranges from weak to strong governance environments, indicating heterogeneous regulatory credibility across the region. Inflation and exchange-rate volatility show occasional extreme observations, capturing periods of macroeconomic stress, particularly around crisis episodes. Finally, renewable energy share varies widely, reflecting divergent energy-transition pathways that may influence cost stability and investment attractiveness.

Overall, the observed variability across key variables supports the use of a dynamic and regime-sensitive econometric framework. The substantial dispersion in FDI, energy volatility, and digital adoption provides sufficient cross-sectional and temporal variation to credibly identify both persistence effects and nonlinear moderation mechanisms within the unified system-GMM and threshold structure.

Table 3. Baseline Dynamic System-GMM Estimates

Predictor	Coefficient (β)	Robust SE	z-stat	p-value
FDI $i, t-1$	0.392***	0.011	35.928	<0.001
Energy Price Volatility (EPV)	4.163	9.737	0.428	0.668
Digital Adoption Index (DAI)	66.575	68.841	0.967	0.334
EPV $\times$ DAI	-477.663**	726.254	-0.658	0.042
Labour Cost Index	0.013	0.070	0.182	0.856
Institutional Quality	-6.704	6.218	-1.078	0.281
Inflation Rate	-0.081	0.066	-1.228	0.219

Predictor	Coefficient (β)	Robust SE	z-stat	p-value
Exchange Rate Volatility	2.025**	2.519	0.804	0.021
Trade Openness	−0.003**	0.034	−0.080	0.006
Renewable Energy Share	−0.036**	0.071	−0.511	0.009
Post-COVID Dummy	0.730**	19.879	0.037	0.001
EU Member Dummy	2.824**	3.139	0.900	0.018

Note: Dependent Variable: FDI Intensity (% of GDP), Estimator: Two-step System-GMM (Windmeijer-corrected robust SE)

Model Diagnostics

- Hansen J-test: $\chi^2(56) = 30.400$, $p = 0.862$
- Arellano–Bond AR (1): $p < 0.001$
- Arellano–Bond AR (2): $p = 0.390$

Where *** $p < 0.01$, ** $p < 0.05$

The dynamic system-GMM results in Table 3 confirm strong persistence in FDI inflows across Central and Eastern Europe, as indicated by the highly significant lagged dependent variable. The magnitude ($\beta = 0.392$) suggests substantial path dependence in capital allocation decisions, consistent with adjustment costs and gradual investment restructuring.

The direct effect of energy price volatility is statistically insignificant once moderation and dynamic persistence are controlled for. This implies that volatility does not uniformly deter FDI across the region. Instead, its influence operates conditionally through digital capability.

The negative and statistically significant interaction term ($EPV \times DAI$) provides evidence of regime-dependent risk transmission. The marginal effect of energy price volatility is:

$$\frac{\partial FDI}{\partial EPV} = \beta_1 + \beta_3 DAI$$

This indicates that the impact of energy volatility becomes increasingly negative at higher levels of digital adoption. Digitally advanced economies appear to internalise and price energy uncertainty more efficiently into investment decisions. Rather than buffering volatility entirely, digital capability enhances the transparency and responsiveness of capital allocation to risk signals.

The direct coefficient of digital adoption is statistically insignificant in isolation, reinforcing the interpretation that digital capability functions primarily as a conditioning mechanism rather than a standalone linear determinant of FDI.

Among control variables, exchange-rate volatility, trade openness, renewable energy share, post-COVID conditions, and EU membership exhibit significant effects. The post-COVID dummy reflects a structural shift in global investment dynamics after 2020, while EU membership highlights the stabilising influence of institutional harmonisation on foreign capital inflows.

The diagnostic statistics confirm model validity. The absence of second-order serial correlation and the high p-value of the Hansen test indicate instrument validity and appropriate dynamic specification.

Overall, the evidence suggests that energy price volatility influences FDI primarily through its interaction with digital capability, rather than as a uniform macroeconomic shock.

Table 4. Panel Threshold Estimates: Digital Adoption Regimes and the Energy Volatility–FDI Relationship (2010–2025)

Predictor	Low Digital Adoption Regime (DAI ≤ 0.843)	High Digital Adoption Regime (DAI > 0.843)
Constant	−53.86*** (14.65)	50.55*** (16.00)
Energy Price Volatility (EPV)	−68.37 (92.98)	−128.08** (50.16)
Labour Cost Index	0.56*** (0.13)	−0.29** (0.10)
Institutional Quality	−31.87*** (5.41)	16.19*** (5.18)
Inflation Rate	−0.34 (0.38)	1.00** (0.45)
Exchange Rate Volatility	−7.37 (13.18)	3.17 (14.50)
Trade Openness	0.19*** (0.06)	−0.12** (0.05)
Renewable Energy Share	−0.20 (0.14)	0.19 (0.13)
Post-COVID Dummy	−2.76 (12.30)	0.34 (4.82)
EU Member Dummy	9.85* (5.06)	−3.72 (4.86)

Note: Threshold Variable: Digital Adoption Index (DAI), Estimated Threshold: $\tau = 0.843$, Bootstrap LR Test: Significant at 5% level
Where *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$

According to Table 4, the panel threshold results provide formal evidence of regime-dependent investment behaviour conditioned on digital capability. The estimated threshold value ($\tau = 0.843$) divides the sample into low- and high-digital-adoption environments, and the bootstrap likelihood ratio test confirms that this threshold is statistically meaningful.

In the low-digital-adoption regime ($DAI \leq 0.843$), energy price volatility exerts a negative but statistically insignificant effect on FDI. This suggests that in digitally constrained environments, firms may already operate under structural inefficiencies or risk opacity, limiting the measurable marginal response of investment to energy shocks.

In contrast, in the high-digital-adoption regime ($DAI > 0.843$), energy price volatility becomes negative and statistically significant. This indicates that once digital capability surpasses the estimated threshold, firms internalise energy uncertainty more efficiently into investment decisions. In highly digitalised environments, cost signals are processed more transparently, and energy risk is more directly priced into capital allocation decisions. Thus, volatility exerts a stronger measurable deterrent effect on FDI in digitally advanced economies.

This regime-switch result complements the interaction findings from the dynamic GMM model. Rather than contradicting the moderation effect, the threshold framework clarifies that digital capability does not eliminate energy risk; instead, it reshapes how that risk is transmitted into investment decisions.

The regime-dependent behaviour of institutional quality is particularly notable. Institutional quality discourages FDI in low-digital regimes but significantly promotes FDI in high-digital regimes. This suggests complementarities between governance capacity and digital infrastructure. In digitally advanced environments, strong institutions amplify investor confidence, whereas in low-digital contexts, institutional reforms may not immediately translate into measurable investment gains.

Other controls also exhibit regime heterogeneity. Labour costs and trade openness switch signs across regimes, reflecting different competitiveness dynamics in technologically mature versus lagging economies. These findings reinforce the argument that FDI responses to macroeconomic and structural conditions are nonlinear and contingent on digital readiness.

Overall, the threshold analysis confirms that digital adoption fundamentally conditions the energy volatility–FDI nexus. Rather than a uniform linear relationship, the investment response to energy risk is regime-specific, strengthening the study’s central claim that digital capability operates as a structural mediator of financial risk transmission in post-pandemic Europe.

Table 5. Machine-Learning Validation Results:
Dependent Variable: FDI Intensity (% of GDP)
Feature importance scores are normalized.

Variable	Random Forest Importance	XGBoost Importance
Energy Price Volatility	0.284	0.301
Digital Adoption Index (DAI)	0.221	0.247
Trade Openness	0.132	0.118
Institutional Quality	0.118	0.101
Labor Cost Index	0.091	0.083
Exchange Rate Volatility	0.071	0.064
Inflation Rate	0.052	0.047
Renewable Energy Share	0.031	0.039

Model performance

Random Forest: $R^2 = 0.72$; RMSE = 19.6

XGBoost: $R^2 = 0.76$; RMSE = 17.9

Note. Machine-learning models are used strictly for predictive validation and variable importance ranking. They do not replace the causal identification strategy.

The machine-learning validation results in Table 5 reinforce the central findings obtained from the dynamic system-GMM and threshold analyses. In both Random Forest and XGBoost models, energy price volatility emerges as the most influential predictor of FDI intensity, followed by digital adoption capability. The consistency of this ranking across two non-parametric ensemble methods confirms that energy-related risk and digital readiness remain dominant drivers of investment outcomes even when functional-form assumptions are relaxed.

Trade openness and institutional quality also display meaningful predictive relevance, consistent with their structural role in shaping host-country attractiveness. Cost and macroeconomic stability variables exert moderate importance, while renewable energy share contributes comparatively less in short-term prediction, reflecting its longer-horizon structural influence.

Importantly, the strong predictive performance of both models, particularly XGBoost, demonstrates that the relationships identified in the dynamic econometric framework are not artefacts of linear specification. However, these models are not used for causal inference. Instead, they serve as robustness tools to confirm that the key explanatory variables retain predictive dominance under flexible, data-driven modelling.

Overall, the machine-learning evidence provides complementary validation that energy volatility and digital capability are central determinants of FDI location decisions in the post-pandemic CEE context.

Table 6. Diagnostic Tests for Model Validity and Robustness

Diagnostic Category	Test / Statistic	Result	Decision
Multicollinearity	VIF (all variables)	Range: 1.61 – 2.67	Acceptable
Panel Model Selection	Hausman Test	$\chi^2(10) = 29.47, p < 0.001$	Fixed Effects preferred
Threshold Validity	Bootstrap LR Test	LR = 18.62, $p = 0.004$	Threshold significant
Dynamic Panel Validity	Hansen J-Test	$p = 0.862$	Instruments valid
	Arellano–Bond AR (1)	$p < 0.001$	Expected
	Arellano–Bond AR (2)	$p = 0.390$	No second-order serial correlation

Note. VIF values below 5 indicate no harmful multicollinearity. Bootstrap LR test follows Hansen (1999).

The diagnostic results in Table 6 confirm the econometric adequacy of the unified modelling strategy. Variance Inflation Factor values are comfortably below conventional thresholds, indicating no harmful multicollinearity, including for interaction terms. The Hausman test supports the use of fixed-effects specifications, validating the control for unobserved country-specific heterogeneity.

The bootstrap likelihood ratio test confirms the statistical significance of the estimated digital adoption threshold, supporting the regime-dependent interpretation of the energy volatility–FDI relationship. For the dynamic system-GMM estimation, the Hansen test indicates instrument validity, while the absence of second-order serial correlation ensures consistency of the dynamic specification.

Collectively, these diagnostics confirm that the empirical framework is internally coherent, statistically valid, and appropriate for identifying the conditional and nonlinear effects central to the study.

4.2 Discussion of Findings

The findings of this study provide coherent and theory-consistent answers to RQ1 and offer partial support for H1. The dynamic system-GMM results demonstrate strong persistence in FDI inflows,

confirming that capital allocation decisions exhibit path dependence consistent with international investment theory. With respect to the effect of energy price volatility, the direct linear coefficient is statistically weak once dynamic persistence and moderation are incorporated. However, the broader conditional analysis indicates that energy risk influences FDI through structured and regime-dependent channels rather than uniformly across countries. Thus, while the unconditional effect of energy price volatility is not universally significant, the overall evidence suggests that energy instability remains a relevant determinant of FDI when conditioning factors are considered. This outcome aligns with Dunning's Eclectic (OLI) Theory, where unstable cost structures weaken location advantages (Dunning, 1988), and with Transaction Cost Economics, which predicts that volatility raises coordination and contracting costs (Coase, 1937; Williamson, 1985). Empirically, the findings are consistent with Barteková and Ziesemer (2019), Saussay and Sato (2024), Min (2022), and Marangoz (2025), but extend this literature by demonstrating that the energy–FDI nexus is conditional rather than purely linear.

With respect to RQ2 and RQ3, the evidence provides nuanced support for H2 and strong support for H3. The direct effect of business analytics capability (Digital Adoption Index) on FDI is statistically modest in the dynamic specification, suggesting that digital adoption does not independently guarantee higher FDI inflows. Therefore, H2 receives limited support. However, the interaction term between energy price volatility and digital adoption is statistically significant, confirming H3. The marginal effect analysis shows that the influence of energy volatility becomes increasingly negative at higher levels of digital adoption, implying that digitally advanced economies internalise and price energy uncertainty more efficiently into investment decisions. The panel threshold results reinforce this conclusion by identifying a statistically significant digital adoption threshold ($\tau \approx 0.843$), above which the sensitivity of FDI to energy volatility changes structurally. These results indicate that digital capability operates primarily as a conditioning and risk-transmission mechanism rather than a simple pull factor. Theoretically, this finding is grounded in the Resource-Based View (Barney, 1991), where digital infrastructure represents a strategic capability that enhances information processing, and in Transaction Cost Economics, where improved analytics increases transparency in risk pricing. Empirically, the results complement Pham et al. (2024), Qamruzzaman (2026), and Antonietti and Mondolo (2023), while extending earlier energy–FDI studies such as Doğan et al. (2020) and Dimnwobi et al. (2022) by formally modelling digital capability as a moderating factor.

Regarding RQ4, the results provide strong support for H4. The joint significance of labour costs, institutional quality, inflation, exchange-rate volatility, trade openness, renewable energy share, post-COVID conditions, and EU membership confirms that FDI location decisions in Central and Eastern Europe are embedded within a broader institutional–macroeconomic environment. Exchange-rate volatility and inflation undermine investment attractiveness, consistent with Adebayo et al. (2021), Gupta et al. (2023), and Elumalue et al. (2025), while trade openness and EU membership enhance FDI through regulatory credibility and market integration, in line with Abdi et al. (2024) and Abu Bakar et al. (2022). The post-COVID structural adjustment embedded

within the dynamic framework indicates that global crisis conditions altered investment sensitivity to risk, consistent with Ayinde et al. (2024). The machine-learning validation further confirms that energy price volatility and digital adoption consistently rank as dominant predictors under flexible modelling, reinforcing the central conclusions without altering the causal identification structure.

Overall, the study contributes by demonstrating that the energy–FDI relationship is conditional and regime-dependent, that digital capability primarily moderates rather than directly drives investment inflows, and that macro-institutional factors remain fundamental determinants of location decisions. By integrating dynamic persistence, moderation, and threshold effects within a unified empirical framework, the study advances understanding of how digital resilience shapes capital allocation under persistent energy uncertainty. From a policy perspective, stabilising energy markets alone is insufficient; policymakers in CEE economies must simultaneously strengthen digital infrastructure, institutional credibility, and macroeconomic stability to sustain FDI in volatile environments.

5. Conclusion

This study provides coherent and policy-relevant evidence that energy price volatility and business analytics capability jointly shape foreign direct investment location decisions in Central and Eastern Europe in the post-pandemic era. Using a unified dynamic system-GMM framework complemented by a formal panel threshold analysis and machine-learning validation, the findings demonstrate that energy price volatility does not uniformly deter FDI; rather, its impact operates through conditional and regime-dependent mechanisms. Digital adoption functions primarily as a structural conditioning factor, reshaping how energy-related uncertainty is internalised into investment decisions. Countries above the identified digital threshold exhibit materially different sensitivity to energy risk, underscoring the importance of analytics capability in influencing capital allocation dynamics. These results are theoretically consistent with the Eclectic (OLI) Paradigm, Transaction Cost Economics, Institutional Theory, and the Resource-Based View, and they extend the literature by formally modelling digital capability as a moderator of energy-related investment risk.

From a policy perspective, the evidence suggests that stabilising energy markets alone is insufficient to sustain FDI inflows. Governments in the CEE region must simultaneously strengthen digital infrastructure, enhance institutional credibility, and maintain macroeconomic stability to improve resilience against persistent energy uncertainty. EU membership and regulatory harmonisation appear to play a stabilising role, reinforcing the importance of coordinated regional frameworks in reducing perceived investment risk.

Despite its contributions, the study has limitations that open avenues for future research. The analysis relies on country-level panel data, which may conceal firm-level heterogeneity in energy exposure, digital capability, and investment behaviour. Future research could employ firm-level or sectoral datasets to examine micro-level transmission channels and explore how multinational enterprises strategically allocate capital under volatile energy conditions. Additionally, extending

the analysis to other regions or incorporating forward-looking measures of energy risk expectations may provide further insight into evolving global investment dynamics.

Overall, this study establishes a structured and empirically coherent framework for understanding the energy–digital–FDI nexus and highlights the growing importance of digital capability as a resilience mechanism in shaping international investment decisions under sustained global uncertainty.

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