LITTERA SCRIPTA

Economics

Management

Corporate Finance

Finance and Valuation

2/2025

VŠTE

Littera Scripta

(Economics, Management, Corporate Finance, Finance and Valuation)

Ing. Jakub HORÁK, MBA, PhD. (Editor-in-chief)

Address Editor:

Institute of Technology and Business in České Budějovice

Okružní 517/10

370 01 České Budějovice, Czech Republic

Tel.: +420 387 842 183

e-mail: journal@littera-scripta.com

ISSN 1805-9112 (Online)

Date of issue: December 2025

Periodicity: Twice a year Since 2010

The Journal is indexed in:

- ERIH PLUS (European Reference Index for the Humanities and Social Sciences) – in 2015
- CEJSH (Central European Journal of Social Sciences and Humanities) – in 2015
- EZB (Elektronische Zeitschriftenbibliothek) – in 2017
- GOOGLE SCHOLAR – in 2017
- DOAJ (Directory of Open Access Journals) – in 2019

Content

Does Digital Readiness Shield or Expose Economies? Evidence from Natural Gas Shocks and Volatility in the European Union

Jan Voharčík[1], Bohumil Koutník[2]

[1] DTI University
[2] Institute of Technology and Business in České Budějovice, School of Expertness and Valuation

Abstract

This study analyzes how digital readiness influences economic resilience to natural gas market instability in European Union countries. Using EU panel data from 2017 to 2022, the analysis integrates the Digital Economy and Society Index (DESI), indicators of natural gas price volatility, and macroeconomic outcomes within a two-way fixed-effects framework. Due to data availability, the shock-based analysis (RQ1) covers 27 EU countries, while the volatility-based resilience analysis (RQ2) is conducted for 25 countries. The results show that digital readiness does not uniformly stabilize economic growth. During severe gas market shocks, higher digital readiness is associated with larger short-term GDP contractions, indicating an amplification of shock transmission. In contrast, routine gas price volatility has no significant direct effect on growth. However, when volatility coincides with high energy dependency, digital readiness contributes to greater economic resilience by mitigating adverse growth effects. Robustness tests confirm the stability of these findings, highlighting a non-linear and state-dependent role of digitalization in the energy-growth relationship.

Keywords: Digital readiness, natural gas volatility, economic resilience, energy dependency, European Union.

Introduction

The current expansion of digitalization, which enhances efficiency alongside rapid technological progress, emphasizes the importance of integrating digital tools in the energy sector as part of climate change mitigation strategies. Maslak et al. (2024), highlighted that innovation and digitalization are crucial for a successful energy strategy and sustainable growth in a rapidly evolving world. Hambye-Verbrugghen et al. (2026), pointed out that value-added growth combined with digital technologies affects energy consumption. Jia et al. (2024) found that digitalization significantly increases firms' energy efficiency, particularly in eastern regions and within the manufacturing sector, while technological innovations further strengthen this effect. Tao et al. (2024) notes that the implementation of improved digitalization has a positive impact on energy poverty. Zheng et al. (2025) showed that digitalization strengthens the capacity utilization of energy companies, with the impact being stronger when higher-quality human capital, a more developed digital environment, and greater market vitality are involved.

According to You et al. (2025), digital transformation significantly increases the productivity of energy-intensive enterprises, with the effect being stronger for state-owned and slower-growing firms, particularly in regions with advanced digital infrastructure and the midwestern areas. Tufail et al. (2026) report that digitalization promotes energy efficiency, whereas GDP reduces energy efficiency. Yun (2024) states that digitalization promotes innovation and job creation, while the inefficient use of natural resources may have a negative impact on economic growth. Alofaysan et al. (2024) found that digitalization positively impacts energy efficiency, whereas GDP has an opposite effect. Bergman & Foxon (2025) observed that digitalization alone does not significantly reduce energy demand, as direct energy consumption from information and communication technologies is growing rapidly. Li et al. (2024) found that a higher level of digitalization in a country supports more stable economic development, while strong dependence can hinder growth and economic stability. Adebayo et al. (2025) indicated that digital technologies reduce the amount of money that countries earn less money from natural resources. Zhang et al. (2025) noted that digitalization hurts the consumption of non-renewable energy sources, whereas it has a positive effect on renewable energy sources. Wang et al. (2025) showed that digitalization can significantly improve energy savings in enterprises; for more effective savings, it should be combined with environmental management capabilities.

Despite the growing literature on digitalization, energy efficiency, and economic growth, existing studies predominantly focus on long-term productivity effects, firm-level outcomes, or average macroeconomic relationships, while paying limited attention to how digital readiness conditions short-term macroeconomic responses to energy market instability. In particular, little is known about whether digitalization mitigates or amplifies the economic impact of sudden natural gas market shocks and ongoing price volatility in highly interconnected economies such as the European Union. Moreover, the distinction between discrete energy supply shocks and routine price volatility is rarely examined, despite their potentially different transmission mechanisms. The objective of this study is therefore to examine the role of digital readiness in shaping economic performance and resilience during periods of natural gas market instability, explicitly distinguishing between acute shock events and persistent volatility dynamics. In doing so, the analysis aims to clarify whether digitalization acts primarily as a stabilizing force or as a channel of shock amplification in the EU context.

This motivation leads to the following research questions:

RQ1: What is the impact of digital readiness on the economic performance of EU countries during natural gas market shocks?

RQ2: Do EU countries with higher digitalization levels exhibit greater resilience to fluctuations in natural gas prices and supply?

Data and Methods

Data and Sample Construction for RQ1

To examine RQ1, this study employs an unbalanced panel dataset covering 27 EU member states over the period 2017–2022, yielding 162 country–year observations after data harmonization. Annual GDP growth rates (percentage change) are used as the dependent variable and serve as a macroeconomic indicator of short-term economic performance. Measures of digital readiness are captured through the Digital Economy and Society Index (DESI), which aggregates performance across connectivity, digital public services, human capital, and digital technology integration. DESI is treated as a continuous variable and varies both across countries and over time. Energy vulnerability is proxied using energy dependency, defined as the share of net energy imports in total energy consumption. To facilitate interpretation in interaction models and reduce multicollinearity, energy dependency is mean-centered at the sample level, producing the variable energy_dep_c. This transformation allows estimated interaction effects to be interpreted relative to an average EU country.

Exposure to energy market disturbances is measured using three alternative indicators of natural gas shocks. First, a continuous gas shock index derived from EU-level gas market conditions is assigned uniformly across countries within each year, reflecting the common exposure of EU member states to gas price and supply disruptions. Second, a binary gas crisis dummy is constructed, taking the value one for the years 2021–2022, corresponding to the period of severe gas market stress following post-pandemic recovery and geopolitical tensions. Third, an extreme shock dummy identifies years in which the gas shock index exceeds its 75th percentile, capturing tail-risk exposure. All macroeconomic and structural variables are merged by country and year. Country identifiers follow Eurostat geographic codes, and time effects are controlled using annual fixed effects.

Empirical Strategy

The empirical analysis for RQ1 follows a stepwise fixed-effects modeling strategy, progressing from baseline specifications to higher-order interaction models. This approach allows for transparent identification of conditional relationships while controlling for unobserved heterogeneity. The baseline specification estimates a two-way fixed-effects model with country and year fixed effects, controlling for time-invariant national characteristics (such as institutional quality and geography) and common macroeconomic shocks. The baseline model assesses the direct association between GDP growth, digital readiness, and energy dependency. To examine whether digital readiness conditions the impact of gas market disruptions, the analysis introduces interaction terms between DESI and gas shocks. This interaction model captures whether the marginal effect of gas shocks on GDP growth varies systematically with the level of digital readiness.

The full specification extends this framework by incorporating energy dependency as a moderating variable, resulting in a triple-interaction model between digital readiness, gas shocks, and energy dependency. This allows the analysis to test whether digitally advanced but energy-dependent economies experience different growth responses to gas shocks compared to less digitalized or less energy-dependent countries.

Formally, the main estimating equation is given by:

$$\begin{aligned} \mathrm{GDP}_{it} = \alpha &+ \beta_1 \mathrm{DESI}_{it} + \beta_2 \mathrm{GasShock}_t + \beta_3 \mathrm{EnergyDep}_{it} + \beta_4 (\mathrm{DESI}_{it} \times \mathrm{GasShock}_t) \\ &+ \beta_5 (\mathrm{GasShock}_t \times \mathrm{EnergyDep}_{it}) \\ &+ \beta_6 (\mathrm{DESI}_{it} \times \mathrm{GasShock}_t \times \mathrm{EnergyDep}_{it}) + \mu_i + \lambda_t + \varepsilon_{it} \end{aligned} \tag{1}$$

Where, μ_i denotes country fixed effects and λ_t denotes year fixed effects. All models are estimated using ordinary least squares (OLS) with standard errors clustered at the country level to account for serial correlation and heteroskedasticity within countries over time. Given the presence of multiple interaction terms and fixed effects, variance inflation is monitored, and interpretation focuses on marginal effects rather than raw coefficients.

Marginal Effects and Robustness Design

Because interaction coefficients in nonlinear settings can be difficult to interpret directly, the study emphasizes marginal effects analysis. Marginal effects of gas shocks on GDP growth are computed across the observed range of DESI values and evaluated at low, median, and high levels of energy dependency. Confidence intervals are derived using the delta method and are visualized through marginal effects plots. To ensure robustness, the full interaction framework is re-estimated using alternative gas shock definitions, including crisis-period and extreme-shock dummies. The consistency of signs, magnitudes, and statistical significance across these specifications provides confidence that the results are not driven by a specific operationalization of energy shocks.

Scope and Interpretation

The empirical strategy is designed to identify conditional associations rather than causal effects. While fixed effects and clustered standard errors mitigate several sources of bias, the results should be interpreted as evidence of systematic macroeconomic patterns in the interaction between digital readiness, energy dependency, and gas market stress. This framework is particularly suitable for understanding short-term growth dynamics in the context of large, externally driven energy shocks affecting the European Union as a whole.

Data and Sample Construction for RQ2

The empirical analysis for RQ2 is conducted on an unbalanced panel dataset covering 25 European Union countries over the period 2017–2022, yielding a maximum of 150 country–year observations. The time span is dictated by the availability of harmonized indicators for digitalization, energy dependency, and natural gas market volatility. Annual real GDP growth (in percentage terms) is used as the dependent variable, capturing short-run macroeconomic performance and allowing direct interpretation of resilience during periods of energy market instability.

Key Explanatory Variables

Digital readiness is measured using the Digital Economy and Society Index (DESI), a composite indicator published by the European Commission. DESI captures multiple dimensions of digital development, including connectivity, human capital, digital public services, and the integration of digital technologies into economic activity. Higher DESI values indicate more advanced digital infrastructures and capabilities. Natural gas market volatility is measured using two alternative indicators: gas_vol: annual volatility of natural gas prices, constructed from higher-frequency price data and aggregated to the country–year level. log_gas_vol: logarithmic transformation of gas_vol, employed as a robustness check to reduce skewness and mitigate the influence of extreme volatility spikes. In addition, a lagged volatility measure (log_gas_vol_l1) is introduced in robustness analysis to account for delayed macroeconomic transmission channels. Energy dependency is proxied by energy_dependency, defined as the share of net energy imports in total energy consumption. To facilitate interpretation of interaction effects and reduce multicollinearity, this variable is mean-centered at the sample level, yielding energy_dep_c.

Econometric Framework

To identify the moderating role of digitalization in the relationship between energy market volatility and economic performance, the analysis employs two-way fixed effects (FE) panel regressions with country and year fixed effects. This approach controls for: Time-invariant country-specific characteristics (e.g., institutional quality, geography, long-run industrial structure), and Common time shocks affecting all countries simultaneously (e.g., global business cycles, pandemic effects). Standard errors are clustered at the country level, allowing for arbitrary serial correlation and heteroskedasticity within countries over time.

Baseline Resilience Model

The baseline specification examines whether digital readiness moderates the impact of gas market volatility on GDP growth:

$$\mathrm{GDP\_growth}_{it} = \alpha + \beta_1 \mathrm{DESI}_{it} + \beta_2 \mathrm{GasVol}_{it} + \beta_3 (\mathrm{DESI}_{it} \times \mathrm{GasVol}_{it}) + \gamma_i + \delta_t + \varepsilon_{it} \qquad (2)$$

Where, i denotes country, t denotes year, γ_i captures country fixed effects, δ_t captures year fixed effects. The interaction term β_3 captures whether higher digital readiness dampens or amplifies the macroeconomic impact of gas price volatility.

Extended Model with Energy Dependency

To explicitly test whether energy dependency conditions the resilience effect of digitalization, the baseline model is extended to include a triple interaction:

$$\begin{aligned} \text{GDP\_growth}_{it} = \quad & \alpha + \beta_1 \text{DESI}_{it} + \beta_2 \text{GasVol}_{it} + \beta_3 \text{EnergyDep}_{it} \\ & + \beta_4 (\text{DESI}_{it} \times \text{GasVol}_{it}) + \beta_5 (\text{GasVol}_{it} \times \text{EnergyDep}_{it}) \\ & + \beta_6 (\text{DESI}_{it} \times \text{GasVol}_{it} \times \text{EnergyDep}_{it}) + \gamma_i + \delta_t + \varepsilon_{it} \end{aligned} \quad (3)$$

The coefficient β_6 captures whether the digital resilience channel is stronger or weaker in countries with higher energy import dependence. The Interaction and triple-interaction coefficients cannot be interpreted directly in isolation; the analysis emphasizes: Marginal effects of digital readiness across different levels of gas volatility and energy dependency, and Comparative interpretation between low- and high-dependency countries. This approach avoids misleading inferences based solely on the signs of individual coefficients.

Robustness Checks

To ensure the stability and credibility of the results, two mandatory robustness tests are conducted.

Robustness Test 1: Alternative Volatility Measure

The baseline volatility variable (gas_vol) is replaced with log_gas_vol. This transformation reduces the influence of extreme values and addresses potential non-linearities in the volatility–growth relationship.

Robustness Test 2: Lagged Gas Volatility

To capture delayed macroeconomic effects, the contemporaneous volatility measure is replaced with log_gas_vol_l1, the one-year lag of gas price volatility. This specification tests whether digital resilience operates with a temporal delay rather than instantaneously. Across all robustness specifications, country and year fixed effects and clustered standard errors are retained to ensure consistency.

Results

RQ1: Digital readiness and economic performance during natural gas market shocks (EU, 2017–2022)

1) Sample and variable overview

The final panel contains 162 country–year observations covering EU member states over 2017–2022. Digital readiness (DESI) shows substantial cross-country variation (mean

10.63; range 4.85–17.40). Economic performance (GDP growth) varies widely across years and countries (mean 2.89%; range −10.9% to 16.3%). Energy dependency also shows large dispersion (mean 82.62; range −56.07 to 149.12). The gas shock variable exhibits meaningful variation over time (mean 0.187; range −0.136 to 0.816), supporting its use as a macro stress indicator during the period.

Table 1: Descriptive statistics (EU countries, annual data 2017–2022; N = 162)

Statistic	**desi_conn**	**desi_dps**	**desi_hc**	**desi idt**	**DESI**	**GDP_ growth**	**energy _dependency**	**energy dep_c**	**gas shock**
count	162	162	162	162	162	162	162	162	162
mean	9.404	14.326	11.412	7.375	10.629	2.890	82.625	0.000	0.187
std	3.205	4.186	2.354	2.602	2.645	4.314	34.511	34.511	0.317
min	3.168	1.853	6.869	2.530	4.850	-10.90	-56.066	-138.691	-0.136
25%	6.976	11.621	9.734	5.592	8.844	1.500	77.496	-5.129	0.001
50%	8.937	14.614	11.069	7.167	10.591	2.900	99.008	16.383	0.049
75%	11.245	17.272	12.818	8.895	12.307	5.375	100.229	17.604	0.340
max	19.272	22.795	17.848	14.772	17.399	16.300	149.119	66.494	0.816

Source: Own.

2) Baseline two-way fixed effects model (DESI and energy dependency)

The baseline two-way fixed effects specification (country and year fixed effects; clustered SE by country) does not show a statistically significant association between DESI and GDP growth ($\beta = 0.719$, $p = 0.338$). Energy dependency is positive but statistically weak ($\beta = 0.026$, $p = 0.106$). This indicates that, once country-invariant characteristics and common time shocks are accounted for, digital readiness is not strongly related to growth on its own in this sample window.

Table 2: Baseline two-way fixed effects results (dependent variable: GDP growth)

Variable	Coef.	Std. Err.	p-value
DESI	0.7192	0.7510	0.338
energy dependency	0.0262	0.0162	0.106
Country FE	Yes		
Year FE	Yes		
Clustered SE (country)	Yes		
Observations	162		
R-squared	0.814		
Adj. R-squared	0.766		

Note: Full country and year coefficients are omitted for readability.

Source: Own.

3) Interaction model: DESI × gas shock

When the gas shock measure is introduced and interacted with digital readiness, the interaction term is negative and statistically significant (DESI × gas shock: β = −0.954, p = 0.002). At the same time, DESI becomes positive and significant (β = 2.253, p = 0.002), while the main effect of gas shock is not statistically significant (β = 0.982, p = 0.608). This implies that the marginal effect of a gas shock on GDP growth becomes more negative as digital readiness increases. In other words, the growth sensitivity to gas market disruptions is stronger in more digitally advanced EU economies, conditional on two-way fixed effects.

Table 3: Interaction results: DESI × gas shock (dependent variable: GDP growth)

Variable	Coef.	Std. Err.	p-value
DESI	2.2532	0.7210	0.002
gas shock	0.9818	1.9140	0.608
DESI × gas shock	-0.9537	0.3140	0.002
Country FE	Yes		
Year FE	Yes		
Clustered SE (country)	Yes		
Observations	162		
R-squared	0.830		
Adj. R-squared	0.786		

Note: Full country and year coefficients are omitted for readability.

Source: Own.

4) Triple interaction: DESI × gas shock × energy dependency

Allowing the shock effect to vary jointly by digital readiness and energy dependency does not change the main conclusion. The DESI × gas shock interaction remains negative and significant (β = −0.983, p = 0.002), while the triple interaction DESI × gas shock × energy dependency is not statistically significant (β = 0.002, p = 0.746). Similarly, gas shock × energy dependency is not significant (β = −0.009, p = 0.924). This suggests that the conditional role of DESI in shaping the growth response to gas shocks is present across the sample and is not systematically stronger or weaker in countries with higher energy dependency (within the 2017–2022 annual panel).

Table 4: Triple interaction results: DESI × gas shock × energy dependency (dependent variable: GDP growth)

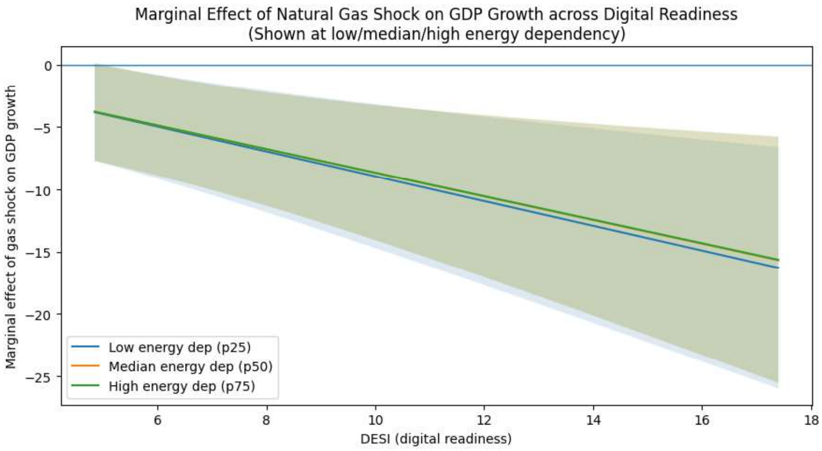
Variable	Coef.	Std. Err.	p-value
DESI	2.2424	0.8360	0.007
gas shock	0.9549	2.0150	0.636
energy_dep_c	0.0227	0.0170	0.183
DESI × gas shock	-0.9829	0.3190	0.002
gas shock × energy_dep_c	-0.0089	0.0930	0.924
DESI × gas shock × energy_dep_c	0.0022	0.0070	0.746
Country FE	Yes		
Year FE	Yes		
Clustered SE (country)	Yes		
Observations	162		
R-squared	0.836		
Adj. R-squared	0.789		

Note: energy_dep_c is mean-centered energy dependency; full country and year coefficients are omitted.

Source: Own.

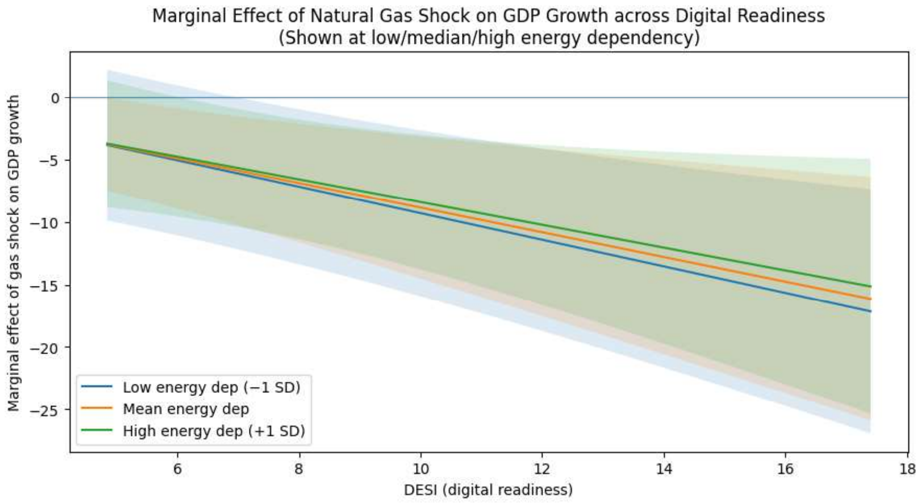
The marginal effects plots convert the interaction terms into an interpretable object: the marginal effect of gas shocks on GDP growth across the DESI distribution. In both specifications (evaluating energy dependency at p25/p50/p75 and at −1 SD/mean/+1 SD), the marginal effect becomes increasingly negative as DESI rises, consistent with the negative DESI × gas shock coefficient. The similarity of lines across different energy dependency levels aligns with the statistically insignificant triple interaction term, indicating that energy dependency does not substantially reshape the DESI-conditioned shock sensitivity in this sample.

Figure 1: Marginal effect of gas shock on GDP growth across digital readiness (DESI), evaluated at low/median/high energy dependency (p25/p50/p75)



Source: Own.

Figure 2: Marginal effect of gas shock on GDP growth across digital readiness (DESI), evaluated at −1 SD, mean, +1 SD of energy dependency



Note: Shaded bands represent delta-method confidence intervals around the marginal effect.

Source: Own.

5) Robustness: alternative shock definitions (crisis dummy and extreme shock dummy)

Using a crisis-period dummy for 2021–2022 yields the same qualitative result: the DESI × crisis interaction remains negative and significant (β = −0.696, p = 0.004), while the crisis dummy itself is not statistically significant (p = 0.942). Similarly, defining an extreme-shock dummy based on the upper tail of the gas shock distribution produces an identical interaction estimate (β = −0.696, p = 0.004), again with the shock dummy itself insignificant (p = 0.942). These robustness checks support the stability of the main result: digital readiness systematically conditions the growth response during gas market stress, regardless of whether shocks are measured continuously or via crisis/extreme dummy definitions.

Table 5: Robustness checks: alternative shock definitions (dependent variable: GDP growth)

Specification	Key interaction	Coef.	Std. Err.	p-value	R^2	N
Crisis dummy (2021–2022)	DESI × gas_crisis	-0.6964	0.2420	0.004	0.834	162
Extreme shock dummy (top-tail)	DESI × gas_shock_high	-0.6964	0.2420	0.004	0.834	162

Note: All models include country and year fixed effects with country-clustered standard errors.
Source: Own.

The results for RQ1 show that digital readiness, by itself, is not a robust predictor of GDP growth once country and year fixed effects are accounted for, but it plays a decisive conditional role during periods of natural gas market stress. Across multiple model specifications and alternative shock definitions, the interaction between digital readiness (DESI) and gas shocks is consistently negative and statistically significant, indicating that the adverse growth effects of gas supply disruptions intensify as digital readiness increases. This pattern is stable across different levels of energy dependency and remains unchanged when shocks are defined using crisis-period or extreme-shock dummies, suggesting that the conditioning role of digitalization is not driven by energy dependency alone. Overall, RQ1 provides clear evidence that digital readiness systematically shapes the macroeconomic transmission of energy shocks in the EU, amplifying short-run GDP sensitivity during periods of natural gas market turbulence rather than insulating economies from such shocks.

RQ2: Does Gas Market Volatility Affect Economic Growth, and Does Digital Readiness Enhance Resilience?

1) Descriptive Evidence on Gas Market Volatility

Before estimating the econometric models, Table 6 summarizes the distributional properties of gas market volatility and gas price returns across EU countries. Gas volatility exhibits substantial cross-country and intertemporal variation, with a mean value of 0.126 and a right-skewed distribution, reflecting episodic periods of extreme instability. Gas mean returns display higher dispersion and both positive and negative realizations, indicating that volatility shocks are not symmetric over time. Table 6 provides initial evidence that gas market instability constitutes a meaningful macroeconomic risk factor rather than a marginal fluctuation.

Table 6: Descriptive Statistics of Gas Market Volatility and Returns

Variable	Mean	Std. Dev.	Min	25%	Median	75%	Max
Gas volatility	0.126	0.128	0.001	0.036	0.078	0.175	0.547
Gas mean return	0.106	0.191	−0.225	−0.024	0.044	0.215	0.609

Source: Own.

2) Baseline Resilience Model: Digital Readiness and Gas Volatility

The baseline two-way fixed effects model evaluates whether gas market volatility directly affects GDP growth and whether digital readiness mitigates this impact. The results, reported in Table 7, indicate that gas volatility on its own does not exert a statistically significant contemporaneous effect on economic growth. Likewise, the interaction between gas volatility and the Digital Economy and Society Index (DESI) is not statistically significant. This finding suggests that short-term fluctuations in gas market volatility do not automatically translate into output losses. Instead, macroeconomic adjustment mechanisms and policy responses may buffer the immediate transmission of volatility shocks. However, the DESI coefficient remains positive, though statistically insignificant, indicating that digital readiness is associated with higher growth on average but does not independently absorb volatility shocks at this stage.

Table 7: Gas Volatility, Digital Readiness, and GDP Growth (Baseline FE Model) (Two-way fixed effects with clustered standard errors)

Variable	Coef.	Std. Err.	p-value
DESI	1.0930	0.789	0.166
gas_vol	1.1421	8.752	0.896
DESI × gas_vol	0.1420	0.730	0.846
energy_dep_c	0.0165	0.016	0.301

Note: Model stats: N = 150, Countries = 25, R^2 = 0.816, Adj. R^2 = 0.764

Source: Own.

3) Triple Interaction: Energy Dependency and Conditional Vulnerability

To examine whether vulnerability depends on structural energy exposure, the model is extended to include energy dependency and a triple interaction term. Results in Table 8 show that neither the two-way nor the three-way interaction terms are statistically significant. This implies that the economic impact of gas volatility is not uniform across energy-dependent economies, but neither does digital readiness alone guarantee insulation from volatility shocks. Instead, resilience appears to operate through broader institutional and policy channels rather than through direct digital–energy interactions. Importantly, model fit remains stable across specifications, indicating that the absence of significance is not driven by misspecification or loss of explanatory power.

Table 8: Gas Volatility, Digital Readiness, and Energy Dependency (Triple Interaction Model)

Variable	Coef.	Std. Err.	p-value
DESI	1.2315	0.747	0.099
gas_vol	4.4042	9.218	0.633
energy_dep_c	0.0122	0.017	0.458
DESI × gas_vol	-0.1117	0.860	0.897
gas_vol × energy_dep_c	0.1501	0.238	0.527
DESI × gas_vol × energy_dep_c	-0.0078	0.020	0.698

Note: Model stats: N = 150, Countries = 25, R^2 = 0.819, Adj. R^2 = 0.763

Source: Own.

4) Robustness Analysis

A) Alternative Volatility Measure

As a first robustness check, gas volatility is replaced with its logarithmic transformation. The results, shown in Table 9, reveal a statistically significant interaction between logged gas volatility and energy dependency, indicating that highly energy-dependent economies are more exposed when volatility reaches extreme levels. Moreover, the negative and significant triple interaction term suggests that digital readiness partially offsets this vulnerability. This finding indicates that resilience mechanisms become visible only under amplified volatility conditions, which are not captured by linear specifications.

Table 9: Robustness Check: Logarithmic Gas Volatility

Variable	Coef.	Std. Err.	p-value
DESI	0.8491	0.645	0.188
log_gas_vol	0.0869	0.649	0.893
energy_dep_c	0.0345	0.019	0.063
DESI × log_gas_vol	-0.0047	0.069	0.946
log_gas_vol × energy_dep_c	0.0320	0.008	0.000
DESI × log_gas_vol × energy_dep_c	-0.0027	0.001	0.000

Note: Model stats: N = 150, Countries = 25, R^2 = 0.825, Adj. R^2 = 0.772

Source: Own.

B) Lagged Gas Volatility

A second robustness test introduces lagged gas volatility to capture delayed transmission effects. As reported in Table 10, lagged volatility does not exert a statistically significant direct effect on GDP growth, nor does it significantly interact with digital readiness. This result confirms that gas market volatility primarily represents a contemporaneous risk, with limited persistence once short-term adjustments occur.

Table 10: Robustness Check: Lagged Gas Volatility (t−1)

Variable	Coef.	Std. Err.	p-value
DESI	1.3861	0.770	0.072
log_gas_vol_l1	1.0638	1.036	0.304
energy_dep_c	0.0518	0.030	0.082
DESI × log_gas_vol_l1	-0.0976	0.099	0.324
log_gas_vol_l1 × energy_dep_c	0.0056	0.014	0.684
DESI × log_gas_vol_l1 × energy_dep_c	0.0001	0.002	0.935

Note: Model stats: N = 125, Countries = (not printed in output), R^2 = 0.828, Adj. R^2 = 0.763

Source: Own.

Overall, the results for RQ2 indicate that gas market volatility does not exert a direct or persistent negative impact on economic growth across EU countries. Digital readiness alone does not automatically provide insulation against volatility shocks; however, under conditions of heightened volatility and strong energy dependency, digital capacity contributes to mitigating adverse effects. These findings suggest that economic resilience to energy market instability is conditional rather than universal, emerging primarily when digital readiness interacts with structural exposure to energy risks.

Discussion

Discussion of Results for RQ1

The results for RQ1 provide clear evidence that digital readiness conditions the macroeconomic impact of natural gas market shocks in the European Union, but not in the protective way often assumed in policy discourse. Across all specifications, digital readiness (DESI) does not exhibit a robust direct association with GDP growth once country and year fixed effects are introduced, suggesting that digitalization alone does not mechanically translate into higher short-term economic growth. This finding is consistent with the view that digital capacity is a structural characteristic whose growth effects materialize through longer-term productivity channels rather than immediate output expansion.

However, when natural gas market shocks are introduced, a systematic and robust interaction effect emerges. The negative and statistically significant interaction between DESI and gas shocks indicates that more digitally advanced economies experience a stronger contraction in GDP growth during periods of gas market stress. This result is stable across multiple shock definitions, including continuous shock indices, crisis-period dummies, and extreme-shock indicators. Importantly, the main effect of gas shocks remains insignificant, implying that it is not exposure to shocks per se, but rather how digital readiness reshapes shock transmission, that matters for growth outcomes. The triple-interaction results further show that energy dependency does not fundamentally alter this digital–shock relationship. Neither the gas shock × energy dependency interaction nor the full DESI × gas shock × energy dependency term is statistically significant, and marginal effects plots confirm that the negative DESI-conditioned shock effect is largely invariant across different levels of energy dependency. This suggests that the amplification effect of digital readiness during gas shocks operates through channels other than direct import dependence, potentially through higher exposure of digitally intensive sectors, greater reliance on energy-sensitive data infrastructure, or stronger integration into global value chains that transmit energy price shocks more rapidly.

Taken together, the RQ1 findings challenge the conventional assumption that digitalization automatically enhances macroeconomic resilience to energy disruptions. Instead, digital readiness appears to increase short-term sensitivity to energy shocks, possibly reflecting the energy intensity and systemic interconnectedness of digitally advanced economies. These results highlight an important trade-off: while digitalization supports long-term competitiveness, it may simultaneously heighten vulnerability to abrupt energy market disturbances unless accompanied by complementary energy-security and infrastructure policies.

Discussion of Results for RQ2

The analysis for RQ2 focuses on whether digital readiness enhances resilience to natural gas market volatility, rather than discrete shock events. In contrast to RQ1, the baseline results show that gas market volatility does not exert a statistically significant contemporaneous effect on GDP growth, nor does it significantly interact with digital readiness in standard two-way fixed effects models. This indicates that EU economies, on average, are able to absorb routine fluctuations in gas prices without immediate output losses, likely due to price-smoothing mechanisms, contractual arrangements, and short-run policy responses. The absence of a significant DESI × gas volatility interaction in the baseline and triple-interaction specifications suggests that digital readiness alone does not systematically dampen or amplify the growth effects of moderate gas price volatility. Energy dependency also remains statistically insignificant in these models, reinforcing the interpretation that volatility, unlike sharp market disruptions, does not automatically translate into macroeconomic instability.

However, the robustness analysis reveals an important nuance. When gas volatility is transformed logarithmically to emphasize extreme volatility episodes, the interaction between volatility and energy dependency becomes positive and significant, indicating that highly energy-dependent economies are more exposed under severe volatility conditions. Crucially, the negative and statistically significant triple interaction between digital readiness, extreme volatility, and energy dependency suggests that digital capacity partially mitigates vulnerability when volatility reaches unusually high levels. This effect does not appear in linear or lagged specifications, implying that digital resilience mechanisms activate primarily under stress-intensive, non-linear conditions.

The lagged volatility models further indicate that volatility shocks do not exhibit strong persistence, as neither direct nor interaction effects remain significant when volatility is lagged by one year. This supports the interpretation that gas price volatility represents a short-lived macroeconomic disturbance, with limited delayed transmission once immediate adjustments occur.

Overall, the RQ2 results paint a more conditional picture of resilience. Digital readiness does not universally shield economies from energy price volatility, but it plays a stabilizing role in highly exposed economies during extreme volatility episodes. This contrasts with the RQ1 findings, where digitalization amplifies sensitivity to discrete gas shocks, and underscores the importance of distinguishing between sudden market disruptions and ongoing price instability when evaluating economic resilience.

Conclusion

This study examined how digital readiness interacts with energy dependence and natural gas market instability to shape the economic performance and resilience of European Union countries. By combining country-level digitalization indicators with macroeconomic outcomes and multiple measures of natural gas market stress, the analysis provides new empirical evidence on the conditional role of digital capacity in energy-related economic shocks. The findings show that digital readiness does not uniformly enhance economic stability. During periods of acute natural gas market shocks, more digitally advanced economies tend to experience stronger short-term output contractions, suggesting that digital intensity may amplify the transmission of sudden energy disruptions. This effect appears largely independent of national energy dependency levels, indicating that the vulnerability of digitally advanced economies arises not solely from import exposure, but from broader structural and systemic channels linked to energy-intensive digital infrastructure and economic interconnectedness.

In contrast, the analysis of gas market volatility reveals a more nuanced role for digitalization. Routine fluctuations in gas prices do not significantly affect economic growth, nor does digital readiness systematically alter their impact. However, under conditions of extreme volatility and high energy dependency, digital readiness contributes to greater economic resilience, partially offsetting the adverse growth effects associated with severe market instability. These results suggest that digital capacity functions as a stabilizing mechanism only under non-linear, high-stress conditions rather than as a general buffer against energy price variability. Overall, the study highlights a fundamental trade-off in the digital-energy nexus. While digitalization is essential for long-term productivity and competitiveness, it may increase short-term exposure to energy market shocks unless accompanied by complementary investments in energy security, infrastructure resilience, and diversification. From a policy perspective, the findings underscore the need for coordinated digital and energy strategies that recognize the dual role of digital readiness, as both a source of vulnerability and a potential resilience mechanism depending on the nature of energy market disturbances.

Future research could extend this framework by incorporating sector-level energy intensity, firm-level digital adoption, or alternative energy price dynamics to further clarify the channels through which digitalization shapes economic resilience in an increasingly volatile energy environment.

References

Adebayo, T. S., Olanrewaju, V. O., Ozkan, O., & Ali, S. (2025). How Does Digital Technology Influence Natural Resource Use: A Global Perspective. *Computational Economics 66*(4), 3567–3589. https://doi.org/10.1007/s10614-024-10800-4

Alofaysan, H., Radulescu, M., Dembinska, I., & Si Mohammed, K. (2024). The Effect of Digitalization and Green Technology Innovation on Energy Efficiency in the European Union. *Energy Exploration & Exploitation 42*(5), 1747–1762. https://doi.org/10.1177/01445987241253621

Bergman, N., & Foxon, T. J. (2025). Policy Implications of Digitalization Pathways for Lower Energy Demand. *Sustainability-Science Practice and Policy 21*(1), 2531628. https://doi.org/10.1080/15487733.2025.2531628

Hambye-Verbrugghen, J., Bianchini, S., Brockway, P. E., Aramendia, E., Heun, M. K., & Marshall, Z. (2026). From Twin Transition to Twice the Burden? Digitalisation, Energy Demand, and Economic Growth. *Ecological Economics 239*, 108747. https://doi.org/10.1016/j.ecolecon.2025.108747

Jia, S., Chen, X., & Jin, J. (2024). Digital Disruption and Energy Efficiency: The Impact of Regional Digitalization on China's Industrial Sector. *Energy 300*, 131542. https://doi.org/10.1016/j.energy.2024.131542

Li, S., Chen, L., Jiang, T., Wang, Y., & Shen, C. (2024). Multidimensional Financial Development and Natural Resources: A Path for Sustainable Development via Natural Resources and Digitalization. *Resources Policy 88*, 104400. https://doi.org/10.1016/j.resourpol.2023.104400

Maslak, O., Grishko, N., Yakovenko, Y., Maslak, M., & Buchashvili, K. (2024). Energy Security and Energy Innovations in the Conditions of Intelligent Systems Development and Digitalisation. *International Journal of Environment and Sustainable Development 23*(4). https://doi.org/10.1504/IJESD.2024.141835

Tao, M., Yan, Z. J., Wu, S., Silva, E., & Qi, L. (2024). Can Digitalization Alleviate China's Energy Poverty? Empirical Investigation and Mechanism Analysis. *Environmental Impact Assessment Review 109*, 107634. https://doi.org/10.1016/j.eiar.2024.107634

Tufail, M., Imran, M., & Song, L. (2026). Unlocking Energy Efficiency Through Digital Platforms: Implications for Sustainable Energy Transition. *Renewable Energy 256*, 124503. https://doi.org/10.1016/j.renene.2025.124503

Wang, Z., Ortiz, J., Li, Y., & Shi, L. (2025). Cross Level Effects of Digitalization and Environment Management on Energy Savings in Chinese Manufacturing Firms. *Energy & Environment*. https://doi.org/10.1177/0958305X251403065

You, W., Chen, J., & Lee, C.-C. (2025). Driving Total Factor Productivity Through Digitalization? Evidence From High Energy Consuming Enterprises in China. *Journal of Asian Economics 100*, 102022. https://doi.org/10.1016/j.asieco.2025.102022

Yun, N. (2024). Resources Curse via Natural Resources Utilization: Linking Digitalization and Resources Markets for Economy Perspective. *Resources Policy 90*, 104774. https://doi.org/10.1016/j.resourpol.2024.104774

Zhang, Y., Gong, J., & Liu, X. (2025). Assessing the Effects of Digitalization on the Amenity of Clean Energy Supply Chains: Policy Insights From OECD Countries. *Energy Economics 143*, 108273. https://doi.org/10.1016/j.eneco.2025.108273

Zheng, X., Zou, F., Liu, Z., & Nepal, R. (2025). How Does Digitalization Affect Capacity Utilization in the Energy Sector? Evidence From China. *Energy Economics 144*, 108337. https://doi.org/10.1016/j.eneco.2025.108337

Contact address of the authors:

Mgr. Jan Voharčík, DTI University, Sládkovičova 533/20, 01841 Dubnica and Váhom, Slovak Republic, e-mail: voharcik@mail.vstecb.cz

JUDr. Bohumil Koutník, Ph.D., Institute of Technology and Business in České Budějovice, School of Expertness and Valuation, Okružní 517/10, 37001 České Budějovice, Czech Republic, e-mail: 37449@mail.vstecb.cz