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Energy security and economic growth: Lessons from recent energy shocks in the EU

Violeta Klyviene

Technical Annex

The ESSI methodology

Jansen et al. (2004) proposed a dual concept Shannon-Wiener diversity index:

$$ESSI = -\sum_{i=1}^{M}[c_i \times p_i \times \ln(p_i)] \quad (1)$$

where:

$c_i = 1 - m_i(1 - \frac{S_i^m}{S_i^{m,max}})$

p_i = share of primary energy source i in total consumption

i = 1, M (primary energy sources index)

c_i = correction factor to p_i

mi = share of net import in primary energy supply of source i

$S_i^m = -\sum_{j=1}^{N}[h_j m_{ij} \times \ln(m_{ij})]$ (Shannon index of import flows of resource i)

j = 1, N (regions of import of energy sources)

$S_i^{m,max}$= ln(N) (maximum value of Shannon index of import flows of resource i)

h_j = extent of political stability in region j, ranging from 0 (extremely unstable) to 1 (extremely stable)

The index is constructed by using annual data from Eurostat energy statistics, World Bank and United Nations databases. Along with fossil fuels (oil, gas, and coal), the analysis also covers nuclear power and renewable energy sources. The latter is divided into hydro power, traditional renewables (solid biofuel and charcoal), and modern renewable energy sources (wind, solar, liquid biofuels, biogas, geothermal, marine, and renewable waste[1]. While the International Energy Agency (IEA) categorises hydropower as a modern renewable energy source, we have chosen to assess it separately to capture the additional effects stemming from climate change.

Furthermore, energy trade balances are considered between the euro area countries and thirteen other world regions and are based on the annual imports of various energy sources such as crude oil, natural gas, and solid fossil fuels from 165 countries[2] located in important fossil fuel exporting regions. It should be noted that imports are limited to crude oil only as oil products do not reflect the actual

[1]International Energy Agency. (2023). SDG7: Data and projections – Modern renewables. https://www.iea.org/reports/sdg7-data-and-projections/modern-renewables:

[2]Countries are grouped into selected regions based on location (same geographically specified area). Some of the largest countries, such as the US, Canada, and Russia, are listed separately due to their importance to energy trading.

share of primary energy imports from the country of origin. Therefore, for countries that do not have their own oil refining facilities, additional assumptions have been made[3]. The final steps of the ESSI included the calculation of the political risks in the thirteen selected regions. Political stability was measured based on the World Bank Stability and Absence of Violence/Terrorism indicators (2010) and weighted according to each country's population share in the specific region (Kaufmann et al. 2010).

The extended Cobb-Douglas production function:

$$Y_{i,t} = A_{i,t} \cdot K_{i,t}^{\alpha} \cdot L_{i,t}^{\beta} \cdot E_{i,t}^{\gamma} \quad (2)$$

Where:

$A_{i,t}$ – total factor productivity for country i at time t ,

$K_{i,t}$- capital input for country i at time t ,

$L_{i,t}$-labour input for country i at time t ,

$E_{i,t}$- energy input for country i at time t ,

α, β, γ- output elasticities of capital, labour, and energy

Nonlinear Autoregressive Distributed Lag (NARDL) (3)

$$\Delta \ln (Y_{i,t}) = \varphi\left[\ln (Y_{i,t-1}) - \beta_1 \ln (LF_{i,t-1}) - \beta_2 \ln (CF_{i,t-1}) - \beta_3 ESSI_{i,t-1}^{+} - \beta_4 ESSI_{i,t-1}^{-} - c\right] +$$

$$+ \sum_{k=0}^{q_1-1} \alpha_{1,k} \Delta \ln (LF_{i,t-k}) + \sum_{k=0}^{q_2-1} \alpha_{2,k} \Delta \ln (CF_{it,k}) + \sum_{k=0}^{q_3-1} \alpha_{3,k} \Delta ESSI_{i,t-k}^{+} + \sum_{k=0}^{q_4-1} \Delta ESI_{i,t-k}^{-} +$$

$$+ CCE\ term + \varepsilon_{i,t}$$

Where:

- $\ln(Y_{i,t})$, $\ln(LF_{i,t})$, $\ln(CF_{i,t})$ – natural logarithm of real GDP, labour force and gross fixed capital formation for country i at time t ,
- $ESSI_{i,t}^{+/-}$ – cumulative positive/negative changes in the ESSI,
- c – intercept,
- φ – error-correction speed,
- β_j – long-run coefficients,
- $\alpha_{j,k}$– short run coefficients,
- q_j– number of lags,
- $CCE\ term$– cross-sectional averages for common factors,
- $\varepsilon_{i,t}$– error term.

[3]Following Eurostat's recommendation, these assumptions were applied both to countries that did not report imports from Russia and to periods with missing or unreported data: for Estonia, 80% of imports from Latvia are assumed to originate from Russia; for Austria, 80% of net imports are assumed to be Russian; for Slovenia, 80% of imports from Austria are attributed to Russia; and for Finland, 80% of imports from Estonia are attributed to Russia.

Panel unit root and cointegration tests confirm that the variables are suitable for NARDL analysis: they are either stationary (I (0)) or integrated of order one (I (1)), and most countries show evidence of a stable long-run relationship among the variables (see Tables 1 to 2).

Table 1. Summary of Unit Root Tests CIPS Unit Root Tests (Akaike Information Criterion)

Variable	Model Specification	CIPS Statistic	P-value	Levels	Country-level stationarity
Log GDP	Non	-5.409	< 0.01	Yes***	8/27
	Intercept	0.000	≥0.10	No	0/27
	Intercept + Trend	-2.633	< 0.10	Yes*	3/27
Log Gross Fixed Capital Formation	Non	-1.979	<0.01	Yes***	6/27
	Intercept	0.000	≥0.10	No	0/27
	Intercept + Trend	-2.855	<0.01	Yes**	7/27
Energy security index (ESSI)	Non	-1.376	≥0.10	No	7/27
	Intercept	0.000	≥0.10	No	0/27
	Intercept + Trend	-2.658	<0.10	No	7/27
Log labour force	Non	-0.498	≥0.10	No	2/27
	Intercept Only	0.000	≥0.10	No	0/27
	Intercept + Trend	-2.633	<0.10	Yes*	8/27

*Note: Panel unit root tests with cross-sectional dependence: Pesaran – CIPS the significance levels are indicated as follows: *** for p < 0.01, ** for p < 0.05, and * for p < 0.10.*

Table 2. Summary of Panel Cointegration Tests

Test	Trend/Intercept Assumption	Statistics	Conclusion
Pedroni residual	Constant	Panel ADF**, Panel PP**, Group ADF**	Strong evidence of cointegration
	Constant and trend	Panel ADF*, Panel PP**, Group ADF*	Strong evidence of cointegration
	Non	Panel ADF**, Panel PP**, Group ADF**	Strong evidence of cointegration
Kao	Constant	ADF**	Strong evidence of cointegration
Johansen Fisher	Constant	Fisher Stat**	At least one cointegrating relationships
	Non	Fisher Stat**	Strong evidence of multiple cointegrating relationships

*Note: The significance levels are indicated as follows: *** for p < 0.01, ** for p < 0.05, and * for p < 0.10.*

The bounds test indicates cointegration for most panels, justifying the use of NARDL model. The Hausman test does not reject the assumption of long-run homogeneity, supporting the pooling of long-run coefficients while allowing for country-specific short-run dynamics and asymmetric responses. The NARDL test further substantiated the long-run significance of the asymmetry (see Tables 3 to 5).

Table 3. Bounds test

Country	F-statistic	Lower and upper bounds:		
		2.200 – 3.090*	2.560 – 3.490**	3.290 – 4.370***
Czech Republic	0.8	No cointegration		
Finland	1.7	No cointegration		
Hungary	1.7	No cointegration		
Ireland	1.2	No cointegration		
Sweden	0.3	No cointegration		
Slovenia	1.0	No cointegration		

*Note: For the listed countries, the bounds test does not support a long-run cointegrating relationship. The significance levels are indicated as follows: *** for p < 0.01, ** for p < 0.05, and * for p < 0.10.*

Table 4. PMG Hausman specification tests

Estimator	Statistic	p-Value
MG (Mean Group)	8.425	0.1343

Note: MG estimator suitability hypothesis rejected

Table 5. NARDL Symmetry tests, long-run

	Statistic	Value	p-Value
ESSI	t-statistic F-statistic Chi - square	2.973 8.835 8.835	0.0031*** 0.0031*** 0.0030***

*Note: Long-run asymmetry is statistically significant (null hypothesis is rejected). The significance levels are indicated as follows: *** for p < 0.01, ** for p < 0.05, and * for p < 0.10.*

Table 6. Short-run coefficients

Variable	**Explicit definition**	**Coefficient**	**T-stat**	**Prob. (p-value)**
COINTEQ*	Error correction term EC_{it-1} (speed of adjustment)	–0.394	–6.90	0.000***
$\Delta \ln LF_{it}$	First difference of labour force	0.042	0.70	0.487
$\Delta \ln LF_{it-1}$	Lagged first difference of labour force	–0.157	–2.03	0.043**
$\Delta \ln CF_{it}$	First difference of investment	0.050	1.99	0.048**
$\Delta \ln CF_{it-1}$	Lagged first difference of investment	–0.018	–1.25	0.213
$\Delta ESSI^{+}_{it}$	Difference of the cumulative positive changes in energy security index	0.07c5	1.08	0.281
$\Delta ESSI^{-}_{it}$	Difference of the cumulative negative changes in energy security index	–0.010	–0.19	0.848
$\Delta ESSI^{+}_{it-1}$	Lagged difference of the cumulative positive changes in energy security index	0.015	0.28	0.776

$\Delta ESSI^{-}_{it-1}$	Lagged difference of the cumulative negative changes in energy security index	–0.069	–1.31	0.100*
CCE_ESSI_P	Cross-section average of positive ESSI changes	0.218	1.71	0.087*
CCE_ESSI_N	Cross-section average of negative ESSI changes	–0.438	–3.84	0.000***
CCE_LF	Cross-section average of labour force	0.990	6.61	0.000***
CCE_CF	Cross-section average of investment-	–0.367	–4.97	0.000***
CCE_Y	Cross-section average of GDP-	0.984	10.12	0.000***

Note: *The significance levels are indicated as follows: *** for p < 0.01, ** for p < 0.05, and * for p < 0.10.*

Source: ESM calculations.

Table 7. NARDL Symmetry tests, short run

Country	Statistic	Value	p-Value
Belgium: Symmetry by sum	t-statistic	2.179	0.0500**
	F-statistic	4.747	0.0500**
	Chi-square	4747	0.0294**
Symmetry by lag	F-statistic	2.550	0.1195
	Chi-square	5.099	0.0781*
Slovenia: Symmetry by Sum	t-statistic	2.144	0.0532*
	F-statistic	4.599	0.0532*
	Chi-square	4.599	0.0320**
Symmetry by lag	F-statistic	2.461	0.1271
	Chi-square	4,922	0.0853*
Slovakia: Symmetry by sum	t-statistic	0.132	0.8966
	F-statistic	0.018	0.8966
	Chi-square	0.018	0.8944
Symmetry by lag	F-statistic	4.073	0.0447**
	Chi-square	8.146	0.0170***
Latvia: Symmetry by sum	t-statistic	0.897	0.3871
	F-statistic	0.805	0.3871
	Chi-square	0.805	0.3695
Symmetry by lag	F-statistic	3.284	0.0728*
	Chi-square	6.569	0.0375**

*Note: Short-run asymmetry is significant in the listed countries (null hypothesis rejected). The significance levels are indicated as follows: *** for p < 0.01, ** for p < 0.05, and * for p < 0.10.*

Although the full EU sample provides a marginal fit to the one of the NARDL requirement, the robustness checks using the reduced country group confirm that the model remains appropriate, with stable and consistent coefficient signs supporting the validity of the results. In addition, two alternative statistical methods (FMOLS and DOLS), commonly used when variables move together over time, were applied. These methods again show a stable long-run relationship between the main variables, and the effects of capital and labour remain positive and statistically strong. The effect of ESSI is also positive in simple models although only one method (FMOLS) finds it statistically significant.

Table 8. Comparison of long-run Coefficients under alternative

Method	PMG_NARDL (short sample)	FMOLS	DOLS
ESSI (positive)	0.004	0.066***	0.049
ESSI (negative)	–0.057***	-	-
Gross Fixed Capital Formation	0.206***	0.404***	0.495***
Labour force	0.238***	0.212***	0.125*

*Note: The significance levels are indicated as follows: *** for p < 0.01, ** for p < 0.05, and * for p < 0.10.*