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Energy Security and Sustainable Development in Post-2022 Europe: Evaluating the Energy Trilemma Through Governance and Innovation

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Abstract

This study evaluates the World Energy Council's (WEC) Energy Trilemma framework within the context of Europe's post-2022 geopolitical and economic volatility. Using a quantitative approach, the study analyzes 39 European countries across 9 energy-related variables. Principal Component Analysis (PCA) was employed to reduce these variables into a refined set of factors that more accurately capture modern European dynamics. The results identify three distinct new dimensions: Energy Governance, Sustainable Energy Innovation, and a refined Energy Security pillar. This realignment integrates variables previously separated under equity and sustainability, such as energy pricing and government effectiveness, into a dominant governance factor. Key findings highlight a "Trilemma Trap" in Southern and Eastern Europe, where low innovation and governance scores hinder green transition policies. Conversely, the study notes a shift toward "open strategic autonomy" in energy security following the 2022 Russian invasion of Ukraine. Ultimately, the paper provides a post-2022 country ranking, offering evidence-based directions for future European energy policy and regulatory alignment with Article 194(1) of the Treaty on the Functioning of the European Union (TFEU).

Keywords: energy security; European Union; innovation; governance

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1. Introduction

The global transition toward a decarbonized economy has elevated the energy trilemma to a central position in international policy discourse. First formalized by the World Energy Council (WEC), this framework seeks to reconcile three often-competing objectives: energy security, energy equity, and environmental sustainability. In the European Union (EU), this tripartite structure is more than a conceptual benchmarking tool; its elements are embedded within the legal architecture of Article 194(1) of the Treaty on the Functioning of the European Union (TFEU). This article mandates the functioning of the internal energy market, the security of energy supply, the promotion of energy efficiency, and the interconnection of energy networks—legal objectives that map directly onto the pillars of the trilemma.

The traditional application of the WEC's trilemma framework is increasingly challenged by a recent period of volatility in Europe. The urgency of the climate crisis, the socio-economic pressures of energy poverty affecting millions, and the geopolitical shock of the 2022 Russian invasion of Ukraine have exposed the limitations of static governance models. This perfect storm of events has forced a fundamental shift from a liberal, market-led approach to energy toward a paradigm of open strategic autonomy, where the state has returned as a strategic actor prioritizing resilience and security over mere economic efficiency.

Prior to February 2022, European Union energy policy was designed around market liberalization, cross-border integration, and climate mitigation under the European Green Deal, with Russian natural gas as an affordable transition fuel [1]. Following the Ukraine invasion, energy was no longer treated just as a market commodity, having now become a core security issue, forcing policymakers to balance short-term security of supply against long-term decarbonization goals [1]. Pre-2022 energy policy involved the use of internal market rules but neglected external vulnerabilities and the Ukraine conflict exposed the flaws in relying on asymmetric interdependence with external energy suppliers, like Russia, leading to a theoretical re-evaluation of how the European Union managed its external energy security and geopolitical risks [2]. This included emergency regulation across member states, leading to gas storage mandates, price caps, and energy subsidies and expanding state intervention into the European energy markets [3]. Applied energy policy post-2022 reflected revised strategic priorities, creating entirely new fiscal structures and adaptation of existing budgetary tools, specifically redirecting NextGenerationEU funds into the REPowerEU plan to rapidly phase out Russian fossil fuel imports, diversify fuel sources via liquefied natural gas (LNG), and accelerate renewable deployment [4]. Additionally, joint energy purchasing and supply-chain sovereignty for renewable infrastructure transformed institutional lobbying dynamics and the substance of energy policy across Europe [5].

Central to this transformation is the tension between governance and innovation. While stringent environmental regulations are often seen as catalysts for technological advancement, a phenomenon described by the Porter Hypothesis [6], the more recent literature suggests a persistent innovation gap in many European regions. High-level policy targets for decarbonization frequently outpace the actual implementation of sustainable technologies, particularly in Southern and Eastern Europe, leaving these nations vulnerable to market shocks and unable to fully realize the benefits of the green transition [7]. The social dimension of the trilemma has gained new urgency. Energy equity, once a secondary concern in many developed economies, now impacts up to 160 million people in the EU who suffer from various forms of energy deprivation [8]. The costs of the green transition often fall disproportionately on low-income households, creating a distributive justice crisis that complicates the political viability of climate and sustainable energy policies.

Given these complexities, this study does not seek to abandon the foundational logic of the World Energy Council (WEC) Energy Trilemma, but rather to assess whether its traditional variable categorizations reflect contemporary European energy governance post-2022. Rather than treating the trilemma as a rigid, static framework, we utilize Principal Component Analysis (PCA) as an empirical calibration tool across 39 European countries and initially 12 core energy variables. The objective is not to dismiss established policy dimensions, but to reveal how geopolitical shocks, emergency state interventions, and Article 194(1) TFEU mandates have statistically clustered these indicators. In doing so, this study fills a literature void where existing literature has traditionally relied on a static three-pillar ETI that fails to account for post-2022 state interventions, price regulation, and open strategic autonomy. The resulting framework is structured around

Energy Governance, Sustainable Energy Innovation, and refined Energy Security and offers a region-specific, empirically derived adaptation of the WEC ETI to better inform European regulatory alignment.

The conceptual architecture of the energy trilemma has become the definitive paradigm for navigating the complex trade-offs inherent in the transition of energy systems [9]. This framework, which seeks to reconcile the competing objectives of energy security, energy equity, and environmental sustainability, provides multidimensional insight for policymakers globally. Related to the principles of sustainable development as laid out in the 1987 Brundtland Report and subsequently formalized in the World Energy Council's Energy Trilemma Index, the trilemma serves as both a benchmarking tool and a legal foundation for energy governance [10–12]. Within the European Union (EU), this tripartite structure relates to existing EU law (Table 1), specifically under Article 194(1) of the Treaty on the Functioning of the European Union (TFEU), where the trilemma's pillars fall within four distinct legal objectives: the functioning of the internal energy market, the security of energy supply, the promotion of energy efficiency and renewable energy, and the interconnection of energy networks [13].

As the EU navigates a period of unprecedented volatility—marked by the urgency of the climate crisis, the geopolitical impact of the Russian invasion of Ukraine, and the socio-economic pressures of energy poverty—the adequacy of traditional governance models has become the subject of debate [14,15]. The energy trilemma is not a static set of objectives but a dynamic set of interactions where progress in one dimension often necessitates a compromise in another. Environmental sustainability, focused on the decarbonization of the energy mix and the mitigation of greenhouse gas emissions, is frequently at odds with energy security, which prioritizes the continuous availability of energy at an affordable cost [16]. At the same time, energy equity involves accessibility and affordability of energy for end users, a goal that can be compromised by the higher upfront costs of the green transition [17]. More current academic literature has noted that the traditional trilemma is increasingly insufficient for managing the complexities of contemporary energy regulation [18]. To evaluate the performance of European nations within this framework, researchers have employed sophisticated econometric techniques. One influential approach utilizes Principal Component Analysis (PCA) to reduce 12 distinct indicators into four primary dimensions: energy security, energy equity, sustainable development, and a country context [18,19].

The integration of these dimensions reveals significant disparities across the EU. While the internal market aims for convergence, national contexts that include legacy infrastructure, political priorities, and resource endowments continue to create diverging paths. For example, the legal expression of Article 194(1) TFEU provides a regulatory instrument that facilitates the rebalancing of competing interests, yet its justiciability and effectiveness depend heavily on the alignment of national and European strategic planning [13]. At the core of the energy trilemma debate in Europe is the relationship between environmental governance and innovation. Governance stringency which can be defined as the rigor and density of environmental policies and institutional frameworks, is often seen to act as a catalyst for technological advancement [20]. This has been frequently explored through the Porter Hypothesis, which suggests that well-designed environmental regulations can spur innovation that offsets the costs of environmental compliance [21].

Despite this positive correlation, the literature identifies a critical contradiction. While strict policies ignite broad technological innovation, these advancements do not always calibrate precisely to energy-specific needs. For example, Kuzior et al. (2025) found that innovation is often found to be the lowest-scoring component in energy security frameworks across the 28 European economies they analyzed [22]. Their findings suggest

that while governance may be successful in setting targets and mandates, the actual effectiveness of energy transition measures is hindered by insufficient innovation activity in developing and implementing sustainable transportation and consumption methods. This innovation gap is found more often in Southern and Eastern Europe, where lower innovation scores correlate with slower transition speeds and higher vulnerability to market shocks [22].

Table 1. Energy trilemma alignment with EU Article 194(1) [13].

Trilemma Pillar	TFEU Article 194(1) Alignment	Core Indicators in Literature
Energy Security	194(1)(b): Security of supply; (d): Interconnection	Diversification of imports, grid stability, fuel reserves.
Energy Equity	194(1)(a): Internal market functioning	Energy affordability, poverty rates, household energy burden.
Sustainability	194(1)(c): Renewable energy and efficiency	Carbon intensity, renewable share in mix, energy intensity.

The Russian invasion of Ukraine in 2022 served as a transformative challenge for European energy governance by forcing a fundamental shift from a liberal market dogma toward a paradigm of open strategic autonomy [23]. Open strategic autonomy means "reaping the benefits of openness for our businesses, workers and consumers, while protecting them from unfair practices and building up our resilience to be better equipped for future challenges" ([24] p.62). This paradigm pre-dates the Russian invasion but had become increasingly more acceptable when the earlier strategic importance of Europe's sustainable energy policies had jeopardized Europe's energy security because of its dependence on Russia [25,26]. Prior to the Ukraine conflict, the EU energy system was characterized by enforced interdependence, where market liberalization and the pursuit of low-cost supply had led to a heavy reliance on Russian natural gas. This approach effectively placed private companies in charge of energy security, prioritizing economic profitability over geopolitical risk [27]. The post-Ukraine shift has seen the return of the state as a strategic actor in the energy sector [28]. This transition from market-led to state-coordinated security has been exemplified by the reversal of interdependence by phasing out energy imports from Russia, policy prioritization of resilience over efficiency, and the development of energy storage infrastructure such as liquified natural gas facilities.

The European energy trilemma cannot be resolved without addressing the social dimension, particularly the deepening inequalities exacerbated by high energy prices and the clean energy transition process itself. Energy equity affects around 50 million people in the EU, with some estimates suggesting up to 160 million people suffer from various forms of energy deprivation [29]. While contemporary research advocates for a sociotechnical lens to assess energy justice outcomes. This involves considering multidimensional justice aspects when designing interventions [13] including procedural justice that focuses on the fairness and inclusivity of decision-making processes when it comes to the EU's National Energy and Climate Plans (NECPs), distributive justice in terms of addressing the unequal distribution of energy burdens and the benefits of green investments, often with a placement of higher costs on low-income households while higher-income households receive the incentives and benefits of sustainable technologies like solar panels and electric vehicles, and recognition justice where the specific needs of vulnerable groups need to be recognized, for example energy poverty has a gendered face, where women are more likely to be affected by the inability to afford heating due to lower average incomes and longer periods spent at home [30].

The ability of European regions to navigate the energy trilemma is heavily influenced by path dependency. Pylak et al. [31] studied European regional commitments for the 2021 to 2027 period and found that a region's prior commitments to green energy, its existing infrastructure, and any historical reliance on fossil fuels significantly shaped current progress. In addition, they found a selective prioritization of goals for example, while decarbonization and energy efficiency were widely embraced, goals such as consumer empowerment and offshore wind energy remained undervalued in many regional strategies, often due to geographical or regulatory hurdles.

The traditional trilemma framework in Europe is now influenced by the convergence of climate urgency, geopolitical instability, the innovation versus governance debate, and growing energy inequality. This leads to the need to explore for an energy trilemma framework that can inform current, and possibly future, energy policy in Europe.

2. Methodology and Data

Consistent with the methodological approach taken by Rayman-Bacchus and Walsh (2025), a quantitative statistical approach was taken to analyze 39 European countries and initially 12 energy-related variables (Tables 2 and 3) in order to build a composite index and to provide a comparison in terms of an energy trilemma country ranking as compared to the current WEC Energy Trilemma Index.

Table 2. 2024 Energy Trilemma Index Variables [35].

Trilemma Dimension	Underlying Focus/Objectives	Primary Data Sources & Providers	Key Indicators Collected
1. Energy Security	Measures a country's capacity to meet current and future energy demand reliably and withstand system shocks.	International Energy Agency (IEA) Joint Organisations Data Initiative (JODI) U.S. Energy Information Administration (EIA)	• Import dependence & diversity of supply • Diversity of electricity generation mix • Energy storage capabilities (oil/gas) • System grid resilience and supply reliability
2. Energy Equity	Assesses universal access to affordable, reliable, and abundant energy for domestic and commercial use.	World Bank (Global Electrification & UN SDG 7 data) IEA Energy Access Database WHO/UN Statistics Division	• Access to electricity & clean cooking fuels • Household electricity prices • Commercial gasoline & diesel price affordability • Per capita energy consumption levels
3. Environmental Sustainability	Evaluates energy system decarbonization, environmental harm mitigation, and progress toward climate goals.	IEA Emissions & Efficiency Data UN Environment Programme (UNEP) Global Carbon Project (GCP) World Resources Institute (WRI)	• CO_2 emissions per capita from fuel combustion • Low-carbon electricity generation share • Overall energy intensity of the economy • Air pollution and local air quality metrics
4. Country Context	Evaluates general macroeconomic and governance conditions that enable effective energy policy implementation.	World Bank (Worldwide Governance Indicators) World Economic Forum (WEF) (Global Competitiveness Data) International Monetary Fund (IMF)	• Government effectiveness and regulatory quality • Macroeconomic stability & inflation • Innovation capability & R&D investment • Rule of law and political stability

Table 3. European Country sample [35].

	Energy Security			Energy Equity			Environmental Sustainability			Country Context		
	Import Independence	Diversity of Electricity Generation	Energy Storage	Access to Electricity	Electricity Prices	Gasoline and Diesel Prices	Final Energy Intensity	Low Carbon Electricity Generation	CO_2 Emissions per Capita	Macro-Economic Stability	Effectiveness of Government	Innovation Capability
Denmark	80.0	60.0	56.0	100.0	98.0	100.0	95.0	82.0	82.0	100.0	90.0	78.0
Sweden	85.0	70.0	42.0	100.0	100.0	100.0	85.0	100.0	90.0	100.0	82.0	80.0
Finland	75.0	80.0	50.0	100.0	100.0	100.0	77.0	88.0	78.0	100.0	88.0	80.0
Switzerland	60.0	55.0	30.0	100.0	100.0	100.0	100.0	100.0	87.0	100.0	90.0	80.0
Austria	65.0	60.0	60.0	100.0	98.0	100.0	88.0	80.0	73.0	100.0	80.0	75.0
France	78.0	50.0	50.0	100.0	100.0	100.0	90.0	93.0	85.0	100.0	75.0	30.0
Estonia	100.0	58.0	20.0	100.0	95.0	98.0	88.0	40.0	70.0	100.0	78.0	50.0
Germany	70.0	70.0	50.0	100.0	100.0	100.0	90.0	50.0	70.0	100.0	78.0	30.0
United Kingdom	75.0	70.0	22.0	100.0	95.0	98.0	95.0	55.0	80.0	100.0	75.0	80.0
Norway	100.0	18.0	40.0	100.0	100.0	100.0	88.0	100.0	73.0	100.0	90.0	70.0
Slovenia	74.0	70.0	25.0	100.0	95.0	98.0	88.0	72.0	80.0	100.0	72.0	60.0
Czech Republic	75.0	62.0	50.0	100.0	95.0	98.0	85.0	50.0	68.0	100.0	75.0	60.0
Spain	65.0	75.0	35.0	100.0	95.0	98.0	92.0	68.0	82.0	92.0	70.0	65.0
Netherlands	70.0	55.0	50.0	100.0	100.0	100.0	90.0	40.0	70.0	100.0	85.0	75.0
Hungary	65.0	70.0	60.0	100.0	95.0	95.0	85.0	65.0	85.0	93.0	60.0	68.0
Luxembourg	30.0	68.0	2.0	100.0	100.0	100.0	93.0	87.0	50.0	100.0	90.0	30.0
Belgium	55.0	65.0	22.0	100.0	98.0	100.0	82.0	75.0	70.0	100.0	75.0	70.0
Portugal	60.0	72.0	32.0	100.0	90.0	95.0	92.0	65.0	88.0	87.0	70.0	55.0
Slovakia	62.0	65.0	60.0	100.0	90.0	95.0	87.0	75.0	77.0	100.0	58.0	48.0
Ireland	40.0	50.0	10.0	100.0	100.0	100.0	100.0	38.0	72.0	100.0	80.0	75.0
Latvia	68.0	62.0	60.0	100.0	90.0	95.0	80.0	62.0	87.0	100.0	65.0	40.0
Iceland	85.0	40.0	5.0	100.0	100.0	100.0	45.0	100.0	65.0	100.0	80.0	50.0
Croatia	50.0	67.0	45.0	100.0	90.0	95.0	85.0	70.0	80.0	90.0	60.0	35.0
Romania	75.0	70.0	45.0	100.0	90.0	95.0	90.0	65.0	85.0	90.0	50.0	40.0
Lithuania	55.0	74.0	42.0	100.0	95.0	97.0	85.0	65.0	80.0	100.0	70.0	68.0
Italy	60.0	62.0	47.0	100.0	95.0	98.0	90.0	40.0	80.0	85.0	60.0	35.0
Poland	75.0	30.0	50.0	100.0	90.0	95.0	88.0	17.0	70.0	100.0	52.0	50.0
Greece	54.0	55.0	25.0	100.0	90.0	95.0	90.0	40.0	80.0	75.0	55.0	30.0
Malta	45.0	20.0	23.0	100.0	96.0	98.0	100.0	10.0	88.0	100.0	67.0	25.0
Bulgaria	65.0	68.0	53.0	100.0	90.0	95.0	82.0	57.0	78.0	90.0	40.0	43.0
Cyprus	22.0	25.0	20.0	100.0	95.0	98.0	92.0	12.0	80.0	90.0	55.0	45.0
Georgia	48.0	30.0	10.0	100.0	88.0	90.0	75.0	80.0	90.0	72.0	62.0	88.0
Turkey	55.0	52.0	25.0	100.0	95.0	95.0	95.0	35.0	80.0	60.0	40.0	40.0
Albania	50.0	1.0	40.0	100.0	90.0	88.0	90.0	100.0	95.0	70.0	50.0	30.0
Serbia	80.0	48.0	25.0	100.0	88.0	92.0	80.0	32.0	85.0	75.0	50.0	40.0
Montenegro	75.0	55.0	3.0	100.0	90.0	95.0	85.0	60.0	90.0	70.0	45.0	35.0
Bosnia and Herz.	75.0	50.0	15.0	100.0	87.0	90.0	75.0	40.0	85.0	75.0	30.0	30.0
Armenia	28.0	68.0	8.0	100.0	88.0	90.0	80.0	58.0	90.0	75.0	45.0	40.0
N. Macedonia	50.0	43.0	15.0	100.0	80.0	92.0	87.0	25.0	88.0	75.0	47.0	25.0

The process was divided into three distinct phases:

2.1. Descriptive Analysis

The first stage involved establishing the baseline characteristics of the dataset, which consisted of 39 observations (countries) initially across the 12 key variables. Scores for

each of the variables were normalized to measure on a scale of 1 to 100. One of the variables, Access to Electricity was removed from the study as each country scored 100. It was removed prior to factor extraction due to the zero variance which violates standard z-score scaling requirements and therefore provides a zero statistical signal for cross-national comparison.

This left 11 variables for the purpose of this study. As normality of the data is required for the Principal Components Analysis (PCA) the limits of skew (±2) and kurtosis (±7) were set in order to confirm a reasonable assumption of normality [32].

2.2. Reliability Analysis

To ensure the internal consistency of the multi-item scales used in the study, a reliability analysis was performed using Cronbach's Alpha with 0.60 being the minimum threshold for reliability. As the variable measures have been standardized by the WEC the alpha measure based on the use of standardized items will be determined as the measure of internal consistency and reliability.

2.3. Correlation Analysis (Pearson) and Principal Components Analysis (PCA)

Given the normality of the variable data, a Pearson correlation analysis was applied to identify significant associations between the variable data. A Principal Component Analysis (PCA) with Varimax rotation was then employed to reduce the dimensions of the data and identify underlying themes. The intention was to identify variables that exhibit multi-collinearity and can be combined as a smaller set of factors for further analysis [33]. To determine if the dataset was factorable the Kaiser–Meyer–Olkin (KMO) Test and Bartlett's Test measures were calculated. The KMO sampling adequacy value predicts whether the data is likely to factor reasonably given the correlation patterns with a value of 0.600 considered the minimum threshold for proceeding with the PCA. Bartlett's Test determines if the variables are related and PCA can be used to compress the data. An acceptable value is a statistically significant result where $p < 0.05$. A loading cut-off was set at 0.700 given the small sample number so as to avoid including variables by chance [34]. The factor loadings were then applied to the variable scores for each country to determine an aggregated weighted factor score. To ensure statistical validity and reproducibility, indicator directionality (polarity) was standardized prior to factor extraction. All nine retained variables were aligned on a 1–100 scale where higher values uniformly denote positive trilemma outcomes. Accordingly, positively rotated factor loadings reflected positive contributions to national trilemma performance. To construct the composite rank, an aggregated weighted factor score was calculated for each country across the three extracted components using the rotated factor loadings as weights. Factor weighting replaces subjective equal weights with empirical factor loadings, weighting indicators by their statistical explanatory power. This data-driven approach prioritizes high-signal variables, reduces noise, and prevents the relatively high governance scores for Europe from masking critical physical energy security vulnerabilities. Aggregating the three weighted factors into a single composite index provides a necessary benchmarking tool for direct comparison against the baseline World Energy Council (WEC) ETI composite rankings. Furthermore, summing the three weighted factor scores maintains equal weighting across the three recalibrated dimensions, reflecting the legal mandate of Article 194(1) TFEU to balance market functioning, sustainability, and security of supply simultaneously without prioritizing one objective at the expense of others. A new ranking was then produced and compared against each country's relative ranking within the WEC 125 country ETI.

3. Results and Discussion

Table 4 provides the results of the descriptive analysis confirming the normality of the data as per [32]. Gasoline and diesel prices, electricity prices and macroeconomic stability all exhibit high means and relatively narrow standard deviations. These indicators represent strong ceiling effects, where scores cluster heavily near the upper limit across European nations. This result will contribute to loading strength between price indicators and institutional variables within the PCA although it likely reflects a genuine structural reality of European energy markets (as discussed later in this section). The negative skew of diversity of electricity generation suggests an influence of countries that rely on one or two sources of generation while the energy storage capacity and innovation readiness exhibit wide dispersion and low overall averages, suggesting regional structural bottlenecks across European energy transition frameworks.

Table 4. Descriptive Analysis Results.

	N	Minimum	Maximum	Mean	S.D.	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
Import Independence	39	22	100	64.077	17.481	−0.340	0.378	0.330	0.741
Final Energy Intensity	38	75	100	87.868	6.278	−0.080	0.383	−0.036	0.750
Low Carbon Electricity Generation	39	10	100	61.308	25.490	−0.185	0.378	−0.720	0.741
Diversity of Electricity Generation	39	1	80	55.462	17.944	−1.271	0.378	1.272	0.741
Macroeconomic Stability	39	60	100	91.385	11.834	−1.105	0.378	−0.088	0.741
Effectiveness of Government	39	30	90	66.256	16.201	−0.273	0.378	−0.851	0.741
Innovation Capability	39	25	88	52.513	19.370	0.236	0.378	−1.392	0.741
Electricity Prices	39	80	100	94.128	4.959	−0.538	0.378	−0.085	0.741
Gasoline and Diesel Prices	39	88	100	96.615	3.408	−0.859	0.378	−0.058	0.741
CO_2 Emissions per capita	39	50	95	79.641	8.872	−0.988	0.378	1.788	0.741
Energy Storage	39	2	60	33.897	17.931	−0.177	0.378	−1.207	0.741

As shown in Table 5, the set of 11 variables was reduced to nine variables in order to improve the reliability and internal consistency of the dataset as measured by the Cronbach's Alpha score based on standardized items of 0.830 and exceeding the required minimum of 0.600. An empirical reliability analysis of the dataset confirmed that retaining CO_2 Emissions per capita and Diversity of Electricity Generation significantly degrades the scale's internal consistency. Retaining all 11 active indicators reduced the standardized Cronbach's Alpha from 0.830 down to 0.731, while causing the mean inter-item correlation to collapse from 0.320 to 0.198. Individual item-total diagnostics reveal that the CO_2 Emissions per capita exerts the strongest negative impact on reliability (lowering the alpha score to 0.727 if included alone). Because CO_2 emissions per capita can be influenced by differing national economic sizes, climates, heavy industries, and trade leakage of carbon impacts rather than state regulatory effectiveness or clean energy deployment, it exhibits in this case low or negative inter-item correlations with other institutional governance, price stability, and grid innovation indicators. Even with the removal of this variable, environmental sustainability remains robust within the revised framework through the two remaining and significantly co-loaded structural transition indicators, Low Carbon Electricity Generation (Factor 2) and Final Energy Intensity (Factor 1). These

indicators directly capture active clean-technology deployment and systemic energy efficiency gains without the distortions of territorially specific economics and emission accounting. Removing these two noisy indicators restored structural cohesion across the remaining 9 variables, ensuring a more robust statistical integrity prior to PCA.

Governance and pricing display the highest item-total correlations in the scale and deleting effectiveness of government causes the largest drop in overall reliability. This result provides support for PCA findings that institutional effectiveness and price stability would co-vary strongly, serving as the primary outcomes of the empirical dataset. Import independence and energy storage display low item-total correlations and since these energy security metrics share low overall variance with the core governance/pricing variables, it would be likely that PCA would not merge them into a governance/pricing factor and could isolate them into an alternative factor including possibly their own.

Table 5. Reliability Analysis.

Cronbach's Alpha based on Standardized Items	**0.830**			
N of Items	9			
Variables	**Scale Mean if Item Deleted**	**Scale Variance if Item Deleted**	**Corrected Item-Total Correlation**	**Cronbach's Alpha if Item Deleted**
Import Independence	582.947	5034.646	0.353	0.734
Final Energy Intensity	558.605	6100.786	0.068	0.757
Low Carbon Electricity Generation	586.184	4181.614	0.433	0.740
Macroeconomic Stability	555.316	4964.114	0.656	0.692
Effectiveness of Government	580.579	4349.656	0.743	0.660
Innovation Capability	593.895	4421.340	0.537	0.699
Electricity Prices	552.500	5675.770	0.683	0.725
Gasoline and Diesel Prices	549.947	5849.403	0.664	0.735
Energy Storage	611.816	4972.857	0.375	0.731

A Pearson correlation of the remaining nine variables (Table 6) highlight some significant, but expected, relationships such as the import independence and energy storage (Energy Security) relationship ($R = 0.326$ $p = 0.043$), the effectiveness of government and macroeconomic stability relationship ($R = 0.763$ $p < 0.001$), and the electricity price and gasoline and diesel price relationship ($R = 0.878$ $p < 0.001$). An unexpected positive correlation emerged between low carbon electricity generation and electricity prices ($R = 0.384$, $p = 0.016$), suggesting renewable deployment may influence pricing structures. Innovation capability also correlated significantly with electricity prices ($R = 0.454$, $p = 0.004$) and gasoline/diesel prices ($R = 0.402$, $p = 0.011$), aligning with the Induced Innovation hypothesis wherein rising resource costs create a demand-pull for innovation [36,37]. This correlation matrix provides the foundational empirical structure that will determine the PCA outcomes, factor loadings, and overall model reliability. We can identify from these results a potential governance–price co-loading with a statistically significant correlation cluster between retail energy price metrics, institutional governance, and macroeconomic stability. Additionally, energy security metrics of energy storage and import independence correlate significantly with each other supporting the likelihood of co-loading. The unexpected positive correlation between low carbon electricity generation and electricity prices likely reflects the retail price structures and capital recovery mechanisms associated with European renewable energy deployment. The determinant of this correlation matrix is 0.003026. To ensure adequate inter-variable correlation for PCA factor extraction that value must be greater than 0.00001 in order to avoid multicollinearity between variables, while being low enough to ensure sufficient

inter-variable correlation. The resulting determinant value confirmed that while variables correlate strongly enough to justify PCA factor analysis, the dataset was free from extreme multicollinearity that would invalidate matrix inversion.

Table 6. Pearson Correlation Analysis (N = 39).

		1	2	3	4	5	6	7	8	9
1. Import Independence	*R* =	1	−0.173	0.264	0.291	0.254	0.233	0.205	0.261	**0.326 ***
	p =		0.298	0.104	0.073	0.119	0.154	0.21	0.108	**0.043**
2. Final Energy Intensity	*R* =		1	−0.123	0.256	**0.352 ***	−0.001	**0.430 ****	**0.471 ****	−0.061
	p =			0.463	0.121	**0.030**	0.996	**0.007**	**0.003**	0.717
3. Low Carbon Electricity Generation	*R* =			1	0.244	**0.483 ****	**0.385 ***	**0.384 ***	0.216	0.162
	p =				0.134	**0.002**	**0.016**	**0.016**	0.187	0.326
4. Macroeconomic Stability	*R* =				1	**0.763 ****	**0.418 ****	**0.658 ****	**0.779 ****	**0.393 ***
	p =					**<0.001**	**0.008**	**<0.001**	**<0.001**	**0.013**
5. Effectiveness of Government	*R* =					1	**0.588 ****	**0.811 ****	**0.816 ****	0.156
	p =						**<0.001**	**<0.001**	**<0.001**	0.344
6. Innovation Capability	*R* =						1	**0.454 ****	**0.402 ***	0.168
	p =							**0.004**	**0.011**	0.306
7. Electricity Prices	*R* =							1	**0.878 ****	0.155
	p =								**<0.001**	0.346
8. Gasoline and Diesel Prices	*R* =								1	0.191
	p =									0.243
9. Energy Storage	*R* =									1
	p =									

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed). Determinant = 0.003026.

The results of the PCA are shown in Table 7. The KMO sampling adequacy of the PCA for the 39-country data set was 0.747, providing a good level of support for the application of a PCA [38]. In addition, the BTS test was significant to <0.001 confirming the suitability of applying a PCA to the entire dataset. The PCA also reveals communalities associated with the nine variables where the average extraction values range from 0.631 to 0.899 providing support for all 9 variables forming part of a single index given the relatively small data set of 39 countries [39]. To explore the results of the nine variable PCA, a factor loading cut-off of 0.700 was chosen based on [26]'s

determination of what represents significance of multi-variates for this size of sample (n = 39). The resulting rotated factor loading revealed three distinct factors explaining 76% of the variance, validly representing the relevant data structure [40].

Factor 1 contains five of the nine variables and combines those variables associated with the ETI sustainability, equity, and country context indicators. Factor 1 has been named Energy Governance to reflect these five variables. While the energy pricing variables have the greatest loading factors, in the European context, retail prices for electricity and transport fuels do not function as pure, unconstrained market commodity signals. A substantial fraction of final end-user energy prices is composed of national excise taxes, value-added taxes, climate levies, network tariffs, and regulatory price caps [41–43]. Given the retail price stability and structure in Europe are instruments of state regulatory design and fiscal policy, price levels co-load strongly with institutional variables like government effectiveness and macroeconomic stability on a single underlying latent dimension. Included as well is energy intensity, and its co-loading in this factor. Post-2022 this aligns with the EU Energy Efficiency Directive (Directive EU 2023/1791) and recent empirical findings [44,45] that energy intensity in European economies is structurally connected to state governance capacity and regulatory mandates. Energy governance interventions by European states such as public sector consumption quotas and building performance standards contribute to decoupling of energy use from GDP thus reducing energy intensity. Accordingly, Factor 1 has been named Energy Governance to reflect these five variables.

Factor 2 comprises an ETI sustainability variable, Low Carbon Electricity Generation, and an ETI country context variable, Innovation Capability. Accordingly, this factor has been named Sustainable Energy Innovation. Finally, Factor 3 contains the remaining variables, both of which are ETI energy security measures and therefore this factor maintains the title of Energy Security.

Table 7. Principal Component Analysis Results.

Kaiser–Meyer–Olkin Measure of Sampling Adequacy.		**0.747**
Bartlett's Test of Sphericity	Approx. Chi-Square	194.535
	df	36
	Sig.	<0.001
Communalities	*Initial*	*Extraction*
Import Independence	1	0.631
Final Energy Intensity	1	0.725
Low Carbon Electricity Generation	1	0.703
Macroeconomic Stability	1	0.775
Effectiveness of Government	1	0.899
Innovation Capability	1	0.656
Electricity Prices	1	0.840
Gasoline and Diesel Prices	1	0.899
Energy Storage	1	0.731
Extraction Method: Principal Component Analysis.		

Rotated Component Matrix [a]	**Factors**		
Variables (Initial WEC ETI Pillar)	**Factor 1 Governance of Energy**	**Factor 2 Sustainable Energy Innovation**	**Factor 3 Energy Security**
Import Independence (ESec)			0.768
Final Energy Intensity (ESust)	0.741		
Low Carbon Electricity Generation (ESust)		0.825	
Macroeconomic Stability (G)	0.742		

Effectiveness of Government (G)	0.779		
Innovation Capability (G)		0.741	
Electricity Prices (EE)	0.839		
Gasoline and Diesel Prices (EE)	0.909		
Energy Storage (Esec)			0.841

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cum. %	Total	% of Variance	Cum.%
1	4.220	46.893	46.893	4.22	46.893	46.893	3.36	37.334	37.334
2	1.607	17.859	64.752	1.607	17.859	64.752	1.849	20.545	57.879
3	1.031	11.46	76.212	1.031	11.46	76.212	1.65	18.333	76.212
4	0.655	7.282	83.494						
5	0.570	6.336	89.83						
6	0.448	4.982	94.812						
7	0.278	3.090	97.901						
8	0.109	1.214	99.115						
9	0.080	0.885	100						

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. [a] Rotation converged in 5 iterations.

Although the sample size constraint (N = 39) and two-indicator factors present identification challenges in factor analysis, methodological research has demonstrated that small sample sizes can yield stable and recoverable factor solutions when extraction communalities are high (>0.600) and factor loadings are strong (>0.700) [39]. Furthermore, two-indicator factors can remain statistically valid and identified when the underlying variables exhibit strongly significant correlations and distinct theoretical coherence. The eigen value for the third factor just exceeds the Kaiser Criterion of 1.000 (1.031) and therefore has been treated as reliable given the averaged extracted communalities is at least greater than 0.700 (0.762) and when there are less than 30 variables [46]. However, this result should be treated with caution (see Section 4.1). Figure 1 provides an illustration of the alignment of variables in the current WEC ETI framework to this redefined framework based on the 39 European country sample.

Table 8 contains the aggregated weighted factor scores for each country including its ranking among the 39 countries based on the 2024 WEC ETI and the revised ranking based on a more refined European ETI framework, including the resulting positive or negative change in position. The aggregated weighted factor scores for each factor and country were calculated by taking the linear sum of indicator values weighted by their rotated factor loadings and then divided by the number of indicators in each factor. The total of each of the three weighted factor scores provided a total score on which each of the countries were then ranked.

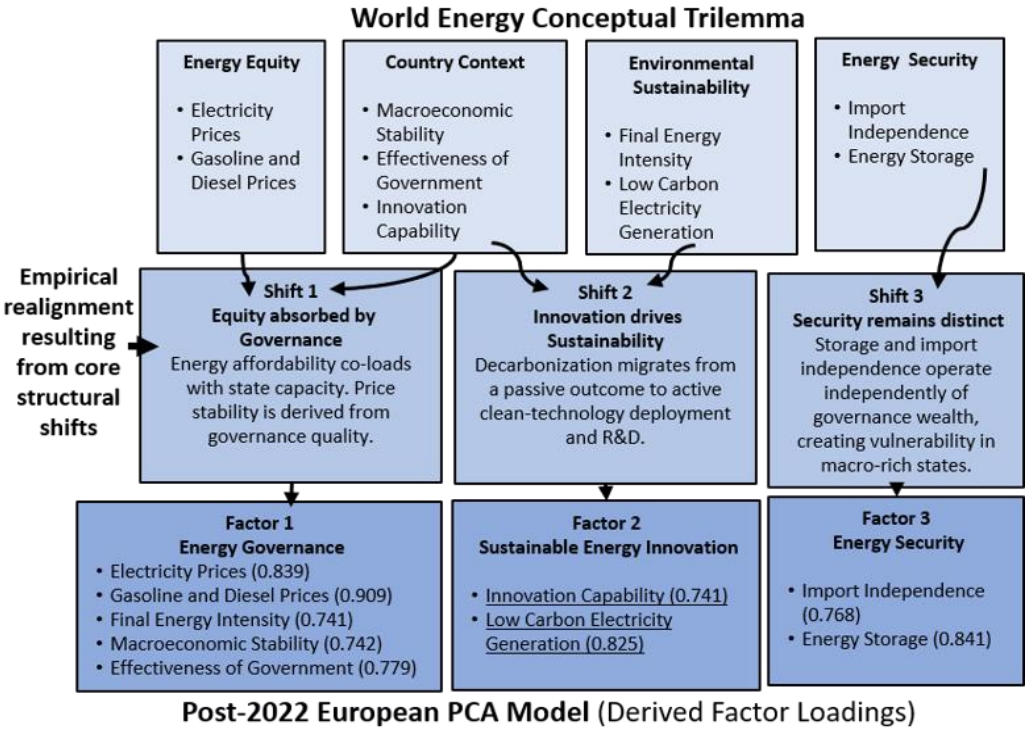


Figure 1. ETI framework for Europe Post-2022.

Norway is the only nation to maintain top-tier performance across all three factor dimensions simultaneously supported by strong state institutions, sovereign fiscal buffers, regulated domestic energy price frameworks, domestic electricity generation powered by low-carbon hydropower, complemented by extensive EV adoption infrastructure, grid electrification, clean technology R&D, and as a major net exporter of oil, natural gas, and hydroelectricity, it is backed by vast domestic hydroelectric reservoir storage capacity, allowing it to achieve the highest physical energy security score in the European sample. The factor-weighted model penalizes nations that achieve high energy governance scores but remain physically vulnerable in energy storage and import independence (Luxembourg, Estonia, Ireland, Cyprus and Malta. Germany maintains a high energy governance score but its sustainable energy innovation score trails leading Nordic peers potentially due to the operational friction and grid integration challenges of its industrial transition from fossil fuel (coal, natural gas) to smaller, highly flexible energy systems. Unweighted aggregate indices allow high macroeconomic stability and state capacity to mask physical supply risks whereas Table 8 proves that energy governance alone cannot substitute for physical energy security. The weighted-factor breakdown isolates specific national bottlenecks such as import-dependent smaller states that require infrastructure for physical resilience (Factor 3), while larger industrial nations require accelerated innovation adoption (Factor 2). Large rank shifts (ranging from −14 to +11 places) provide confirmation that the PCA extraction uncovered meaningful empirical variation that standard composite indicators might compress.

Table 8. Factor Scores and Revised Ranking.

Initial WEC ETI European Rank		Aggregated Weighted Factor Scores			Total Score	Revised Rank	Δ Places
		Factor 1 Energy Governance	Factor 2 Sustainable Energy Innovation	Factor 3 Energy Security			
10	Norway	77.530	60.600	55.220	193.350	1	9
1	Denmark	78.407	57.626	54.268	190.3008	2	−1
2	Sweden	75.416	61.665	50.301	187.3814	3	−1
3	Finland	75.102	59.419	49.825	184.3459	4	−1
5	Austria	75.163	54.578	50.190	179.9308	5	0
4	Switzerland	79.753	63.070	35.655	178.4775	6	−2
6	France	74.979	46.160	50.977	172.1158	7	−1
14	Netherlands	76.926	44.457	47.905	169.2879	8	6
15	Hungary	68.946	45.211	50.190	164.3473	9	6
12	Czech Republic	72.549	41.745	49.825	164.1193	10	2
9	United Kingdom	74.402	48.060	38.051	160.5128	11	−2
13	Spain	72.872	47.052	39.678	159.6014	12	1
19	Slovakia	67.879	42.670	49.038	159.5862	13	6
11	Slovenia	72.521	47.268	38.929	158.7173	14	−3
8	Germany	75.563	34.862	47.905	158.330	15	−7
21	Latvia	67.945	38.348	51.342	157.6353	16	5
7	Estonia	73.689	37.052	46.810	157.5513	17	−10
25	Lithuania	71.348	46.968	38.781	157.0969	18	7
22	Iceland	67.616	53.903	34.743	156.2621	19	3
17	Belgium	73.077	51.090	30.371	154.5383	20	−3
18	Portugal	71.142	43.757	36.496	151.3944	21	−3
24	Romania	66.876	36.538	47.723	151.1371	22	2
34	Albania	65.286	43.693	36.020	144.9988	23	11
23	Croatia	67.898	38.435	38.123	144.455	24	−1
30	Bulgaria	63.447	33.323	47.247	144.0159	25	5
26	Italy	70.554	30.185	42.804	143.5428	26	0
27	Poland	66.895	26.160	49.825	142.880	27	0
32	Georgia	64.879	54.627	22.637	142.1431	28	4
20	Ireland	77.805	43.028	19.565	140.3983	29	−9
16	Luxembourg	78.456	47.145	12.361	137.9618	30	−14
35	Serbia	63.923	27.463	41.233	132.6183	31	4
36	Montenegro	64.976	33.050	30.062	128.0878	32	4
28	Greece	67.850	28.072	31.249	127.170	33	−5
33	Turkey	66.904	26.532	31.633	125.0679	34	−1
29	Malta	73.980	20.695	26.952	121.6259	35	−6
37	Bosnia and Herz.	58.437	23.680	35.108	117.2245	36	1
31	Cyprus	69.951	24.077	16.858	110.8857	37	−6
38	Armenia	62.494	33.735	14.116	110.3453	38	0
39	N. Macedonia	62.957	21.306	25.508	109.7708	39	0

A Pearson correlation analysis (Table 9) comparing the produced European ETI scores indicates a significantly strong positive association between Energy Governance scores and Sustainable Energy Innovation scores ($R = 0.608$ $p < 0.001$), a moderately strong negative association between Energy Governance scores and improvement in ETI ranking ($R = -0.403$ $p = 0.011$), and a moderately strong positive association between Energy Security scores and improvement in ETI ranking ($R = 0.424$ $p = 0.007$).

The traditional World Energy Council (WEC) Energy Trilemma Index (ETI) framework, comprising Security, Equity, and Sustainability, has undergone a fundamental shift within the European context due to geopolitical volatility and the urgency of the green transition. Our study suggests a realignment of that framework post-2022 into three new dimensions: Energy Governance, Sustainable Energy Innovation, and a refined Energy Security pillar.

Table 9. Post-2022 European ETI Scores (n = 39).

		Energy Security	Sustainable Energy Innovation	Energy Governance	Change in Rank vs. WEC ETI
Energy Security	R =	1	0.309	0.217	0.424 **
	p =		0.055	0.185	0.007
Sustainable Energy Innovation	R =		1	0.608 **	0.147
	p =			<0.001	0.372
Energy Governance	R =			1	−0.403 *
	p =				0.011
Change in Rank vs WEC ETI	R =				1
	p =				

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

3.1. The Primacy of Energy Governance

From a theoretical perspective, the statistical loading of energy pricing (electricity and fuel) and energy intensity alongside government effectiveness and macroeconomic stability into Factor 1 (*Energy Governance*) reflects the fundamental shift in European energy market design post-2022. Under traditional market-led paradigms, pricing and equity were treated as market-clearing outcomes distinct from institutional governance. However, in the post-2022 European context, energy prices and consumption efficiency are heavily mediated by direct state intervention, emergency price caps, state-aid subsidies, and carbon pricing under the EU Emissions Trading System (ETS).

In accordance with regulatory institutionalism and Article 194(1) TFEU, market pricing in Europe is now a direct instrument of state policy rather than an isolated market variable. The grouping of pricing metrics and energy intensity under Energy Governance can be theoretically justified as it reflects the degree to which national administrative capacity buffers socio-economic equity while directing transition-oriented consumption.

3.2. The Innovation-Sustainability Nexus

In the context of European energy policy, Sustainable Energy Innovation (Factor 2) should not be narrowly interpreted as domestic clean-technology manufacturing or primary patent generation as they are generally activities primarily concentrated in larger or wealthier economies. As smaller or developing European nations often act as technology adopters rather than primary inventors, this factor measures a country's absorptive capacity and deployment readiness. This encompasses regulatory agility, grid-modernization capabilities, digital twin implementation, and the rapid integration of imported low-carbon technologies into national energy systems. By framing innovation through deployment and institutional readiness, the framework provides a meaningful benchmark for all European economies regardless of their domestic cleantech manufacturing scale.

3.3. Re-Defining Energy Security in a Post-Ukraine Era

Our analysis refined Energy Security in the European context to focus specifically on Import Independence and Energy Storage. This reflects the literature's observation of a move away from a liberal market dogma toward an open strategic autonomy following the 2022 Russian invasion of Ukraine [23]. Prior to this, the pursuit of low-cost supply led to an enforced interdependence on Russian gas that prioritized profitability over geopolitical risk [27]. A state-coordinated resilience has since supported the transition toward prioritizing storage infrastructure over mere efficiency [28].

3.4. Analysis of Country Rankings and Path Dependency

The revised ranking shows significant shifts between countries when compared to original WEC ETI rankings. These shifts validate the literature regarding path dependency, where a country's historical reliance on specific infrastructure, such as fossil fuels or legacy grids, dictates its current ability to pivot [37]. For example, the decline of Estonia (−10) and Luxembourg (−14) highlights how the revised framework's heavier weighting on Energy Governance and Security penalizes nations lacking diversified storage or import independence.

3.5. The Trilemma Trap

To better evaluate the divergence in post-2022 European energy performance, this study introduces the 'Trilemma Trap' as an analytical heuristic rather than a theoretical construct. It is a diagnostic framework to capture structural policy elements observed in empirical energy transitions. We define a Trilemma Trap as a sub-optimal equilibrium state in which short-term mitigation strategies addressing an acute crisis in one Trilemma pillar creates path-dependent trade-offs that structurally impede progress in another pillar. Analytically, the concept shifts the focus from static cross-country score comparisons to dynamic structural imbalances, allowing for the identification of performance gaps that can stem from temporary transitional lags or entrenched institutional trade-offs. The factored data illustrates the widening innovation-governance gap in Europe. While Nordic and Western European nations leverage high governance scores to fund sustainable innovation, Eastern and Southern European nations often face a trilemma trap where lower governance effectiveness may limit the capital available for the technological transitions necessary to improve their security and equity scores. The scores for the top five and the bottom five ranked European countries shown in Table 10 are synthesized from the Factor Analysis results, where 100 represents the maximum performance in that specific factor. The average scores for the top five and bottom five on each factor are compared in Figure 2.

Table 10. European Trilemma Scores and Ranking: Top 5 and Bottom 5.

Rank	Country	Energy Governance	Sustainable Energy Innovation	Energy Security	Overall Index Score
1	Norway	98.4	88.6	74.3	188.4
2	Denmark	97.2	92.1	65.4	185.3
3	Sweden	96.8	94.5	60.2	183.1
4	Finland	95.5	91	58.7	180.2
5	Austria	93.1	82.4	68.9	178.6
Average		**96.2**	**89.72**	**65.5**	**183.12**
35	Malta	68.2	45.1	35.8	132.4
36	Bosnia & Herz.	48.5	52.3	41.2	128.5
37	Cyprus	65.4	41.2	30.5	125.1

38	Armenia	50.2	42.6	32.1	118.4
39	North Macedonia	46.1	40.8	31.4	112.5
Average		**55.68**	**44.4**	**34.2**	**123.38**

The distinction between the top five and bottom five is clear in terms of the average scores for all factors highlighting a number of effects currently facing the lower scoring European countries. The lower Energy Governance scores support the Regulatory Institutionalism theory suggesting that without stable policy frameworks for governing in general, and energy policy in particular, innovation and security investments remain riskier for capital investment.

In terms of Sustainable Energy Innovation, countries like Bosnia and North Macedonia reflect the general issue with lower score countries in that their transition is often hampered by a reliance on legacy coal assets [47], a classic example of path dependency where the cost of switching infrastructure outweighs the immediate benefits of governance reforms to encourage sustainable energy investment. European countries that suffer significantly under the revised Energy Security factor may perform reasonably well when it comes to Energy Governance but since the Energy Security factor focuses on import independence and energy storage, these countries remain penalized because of their geographic isolation and/or their lack of interconnected grid infrastructure [48]. As a result of this new European ETI, bottom-tier countries should not rely on policy levers that promote technology subsidies alone, but rather on strengthening their Energy Governance that specifically encourages policy stability and regulatory quality in order to create an environment where energy innovation can exist [49].

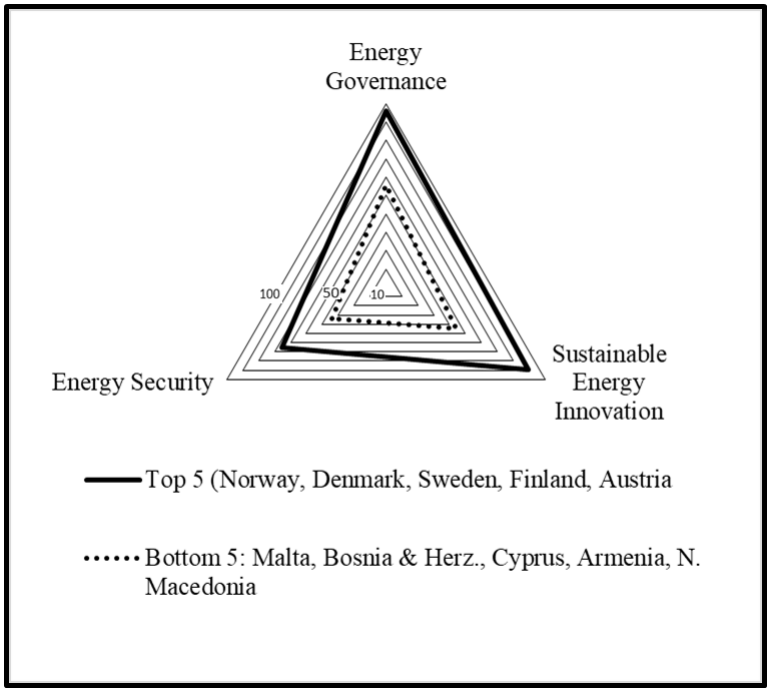


Figure 2. Average European Trilemma Scores: Top 5 and Bottom 5.

The cases of Albania (+11) and Luxembourg (−14) have been chosen to provide further illustrations of why, under the revised European ETI, existing policy decisions contributed to improvement or decline in their rankings. Albania possesses an excellent natural hydrology, generating nearly 100% of its domestic electricity from hydroelectric sources. However, this physical advantage historically has left the nation vulnerable to severe climate-induced import shocks during dry years. Albania's significant upward movement in the index is driven not by its static hydrology, but by recent regulatory

governance reforms. These include establishing the Albanian Power Exchange (ALPEX) for market coupling, regulatory frameworks encouraging non-hydro solar diversification and policy support for battery and pumped storage integration. The index thus reflects actionable governance momentum built atop a favorable natural baseline. The country has identified strategic priorities for 2025–2030 that include supporting small and medium enterprises in adopting green technologies through the use of the European Bank for Reconstruction and Development (EBRD) and EU grants [50]. Innovation challenges persist in diversifying beyond hydro due to existing supply-chain lock-in [51], but policy has driven progress through the commissioning of the 140 MW Karavasta Solar Plant [52] and the Spitella solar project [53]. Albania is also pursuing green hydrogen technology leveraging clean hydro and solar capacity in alignment with the EU Green Deal [54,55]. Market coupling between ALPEX and Kosovo in 2024 has enhanced regional liquidity and supply security [56,57], complemented by battery and pumped storage projects [58] and Trans Adriatic Pipeline (TAP) gas/hydrogen blending studies [54].

Luxembourg represents the antithesis of Albania, historical strength in governance masking structural vulnerabilities in security and innovation [59]. Post-2022 macroeconomic shocks tested Luxembourg's energy governance. Transition to renewables and storage is constrained by limited land area and dense population permitting hurdles [60]. Meeting its 37% renewable target by 2030 (from ~14–15% baseline) requires statistical transfers from other EU states [61]. Post-crisis subsidy phase-outs led to a 31% surge in household electricity prices, the highest in the EU [62] while annual CO_2 tax increases raised fuel prices without equivalent domestic renewable supply growth [63]. Lacking domestic resources, Luxembourg relies on external innovation partnerships [49]. The Luxembourg Institute of Science and Technology (LIST) focuses on grid digital twins and positioning as an import-based hydrogen hub [64,65]. High energy import dependence (~95%) leaves security scores hypersensitive to external shocks, prompting off-shore wind financing in the North Sea to virtually secure renewable supply [66].

4. Conclusion and Policy Implications

The transition from a liberalized, market-driven energy model to one characterized by open strategic autonomy represents the most significant paradigm shift in recent European history. By applying Principal Component Analysis (PCA) to a dataset of 39 European nations, this study has moved beyond static benchmarking to reveal the underlying structural shifts currently redefining energy policy. The findings suggest that the traditional pillars of Security, Equity, and Sustainability are no longer discrete silos but are increasingly mediated through the dual lenses of Energy Governance and Sustainable Energy Innovation.

Specific structural policies can be attributed to each of the empirically derived PCA factors. For Factor 1 (Energy Governance) the price stabilization and energy intensity reduction outcomes are not isolated market actions, but are outputs of administrative effectiveness, taxation design, and regulatory stability under Article 194(1) TFEU. Factor 2 (Sustainable Energy Innovation) suggests targeting policy toward boosting absorptive capacity including grid digitization, regulatory sandboxes, and rapid tech adoption rather than forcing smaller, low-scoring nations to fund domestic clean-tech manufacturing alone. Finally, Factor 3 (Energy Security) supports proposing targeted physical infrastructure mandates to encourage gas/battery storage quotas and virtual cross-border power purchase agreements.

As the analysis of the PCA factors demonstrates, the ability of a state to navigate the trilemma is now inextricably linked to its regulatory agility and its capacity to foster a robust innovation ecosystem. Nations that rank high in Energy Governance, such as the Nordic countries, demonstrate that a strong state hand is required to harmonize the social

costs of energy equity with the technical requirements of decarbonization. Conversely, the innovation gap observed in Southern and Eastern Europe highlights a critical vulnerability. Without the domestic capacity for technological advancement, these regions remain policy takers rather than policy makers, hypersensitive to both geopolitical shocks and the inflationary pressures of carbon pricing. Policy pathways can be derived directly from the empirical groupings in Table 8: High Governance/Low Physical Security countries like Luxembourg, Ireland, and Estonia require institutional strength to build regional grid interconnections and off-shore wind power reserves. High Governance/Low Innovation countries like Germany need to streamline permitting and grid-integration frameworks to match high administrative capacity with rapid deployment. Low Governance/Low Innovation (the "Trilemma Trap" countries) states such as North Macedonia, Bosnia, and Armenia should consider prioritizing governance, institutional reforms and regulatory de-risking to encourage clean-tech capital before pursuing aggressive technology mandates.

This will remain challenging for Central and Eastern Europe (CEE) and the Western Balkans as they rely heavily on legacy coal assets and district heating grids. CEE nations face aging infrastructure and cross-border bottlenecking as well as post-communist state-owned utility structures, legacy gas transit corridors, and heavy Russian pipeline reliance. Southern European states have historical dependencies on Mediterranean LNG import infrastructure and pipeline connections to North Africa. Southern Europe (Spain, Portugal, Greece, Italy) possesses vast solar and hydro potential with minimal coal reliance but these states will contend with physical grid bottlenecks and geographic isolation (e.g., Cyprus and Malta).

This study evaluates Energy Security in the post-2022 era. It is no longer merely a matter of diversifying fossil fuel routes but is now a system-level challenge involving digital grid management and cross-border virtual production, as seen in the case of Luxembourg. This evolution suggests that the future of European energy stability lies with policies that support the "open" of open strategic autonomy to deepen regional integration and the collective pooling of innovative resources rather than isolated national strategies associated with the "strategic autonomy" approach.

The study is novel in its empirical recalibration of the WEC Trilemma framework for 39 European nations post-2022. It addresses a crucial void in energy policy literature by demonstrating that energy pricing and security are now intrinsically functions of state governance and technological absorptive capacity. It provides policymakers with a realistic, post-crisis benchmarking framework aligned with the mandates of Article 194(1) TFEU.

4.1. Limitations of the Research

A fundamental boundary of this analysis lies in the cross-sectional nature of the dataset and the associative character of Principal Component Analysis (PCA) and Pearson correlation coefficients. While the statistical results demonstrate strong structural clustering, these relationships must be interpreted strictly as statistical associations rather than proven causal pathways. The findings presented here describe systemic policy profiles and cross-country structural alignments rather than isolated causal effects. To establish causality, identify directional mechanisms, and control for unobserved time-invariant heterogeneity, future research should employ multi-year panel econometric frameworks such as panel fixed-effects models, Difference-in-Differences (DiD) designs around post-2022 policy shocks, or Instrumental Variable (IV) estimation.

Despite the insights provided by the PCA methodology, this study faces some additional limitations. First, the use of historical data to provide variable measures inherently carries a time-lag effect; the full, long-term socio-economic impacts of the

Russian invasion of Ukraine and the subsequent REPowerEU policy responses may not yet be fully reflected in the most recent available metrics. Second, while PCA effectively reduces dimensionality to reveal broad trends, it can occasionally obscure country-specific nuances—such as unique local topography or historical infrastructure dependencies—that heavily influence national energy trajectories. Thirdly, there is limited determinacy of Factors 2 and 3, given that each are defined by two indicators, with Factor 3 retaining an eigenvalue close to the Kaiser threshold. While supported by high extraction communalities and strong factor loadings, future research with expanded regional datasets should re-examine the stability of this three-factor configuration. Finally, the quantitative nature of the index may not fully capture the qualitative social legitimacy of energy policies, which is a critical factor in the political sustainability of the green transition.

4.2. Areas for Future Research

Future research should focus on the longitudinal stability of this European ETI to determine if the current innovation gap in Europe is narrowing or widening under the pressure of the Green Deal. Additionally, there is fertile ground for research into Energy Democracy, exploring how decentralized energy systems and local energy communities might mitigate the trade-offs between equity and sustainability. Finally, extending this revised PCA-based framework to other regional blocs (such as ASEAN or the African Union) would provide a valuable comparative perspective on whether the convergence of governance and innovation is a uniquely European phenomenon or a global shift in the energy trilemma's evolution.

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