Examining the Causal Relationship Between Cryptocurrencies and Energy Consumption in D8 Countries: A Bootstrap Panel Granger Causality Approach

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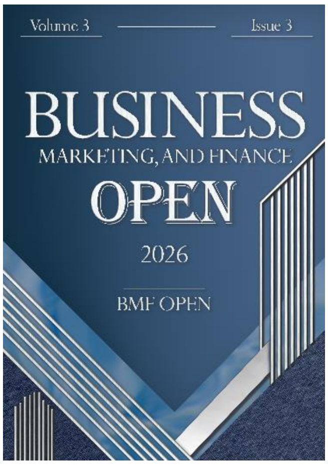

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Abstract: The exponential growth of the cryptocurrency market has raised increasing concerns regarding its environmental consequences, particularly energy consumption. The existing literature has predominantly focused on energy-intensive cryptocurrencies while overlooking the asymmetric effects of non-energy-intensive cryptocurrencies and the moderating role of institutions in developing countries. Using a mixed-methods approach, this study examined the causal relationship between energy-intensive and non-energy-intensive cryptocurrencies and energy consumption in D8 countries over the 2015–2024 period. In the quantitative phase, following second-generation diagnostic tests, the Kónya bootstrap panel causality test and Seemingly Unrelated Regression (SUR) estimation were employed. In the qualitative phase, comparative institutional analysis was used to interpret the findings. The results revealed profound structural heterogeneity. Causality running from Bitcoin to energy consumption was confirmed in Iran (subsidy-based), Malaysia (market-oriented), and Nigeria (inflation-hedging), whereas the direction of causality was reversed in Türkiye, Indonesia, and Bangladesh. No significant causal relationship was observed in Egypt or Pakistan. For the first time, the paradox of non-energy-intensive cryptocurrencies was documented: these cryptocurrencies affected energy consumption through indirect channels—namely, digital ecosystem development and complementarity with energy-intensive cryptocurrencies—in countries characterized by low energy efficiency. The share of fossil fuels exhibited the largest coefficient in the energy consumption equation. The cryptocurrency–energy nexus in developing countries is therefore highly context-dependent and contingent upon institutional structures. A "one-size-fits-all" policy approach is rejected, and policymakers should adopt differentiated strategies based on the proposed typology—cryptocurrency-driven, energy-driven, and disconnected systems. The findings also challenge the "green cryptocurrency" narrative and underscore the necessity of evaluating the entire life cycle of the digital ecosystem in energy policymaking.

Keywords: cryptocurrency, energy consumption, bootstrap panel causality, comparative institutional analysis, D8 countries, mixed-methods methodology.

1. Introduction

The rapid expansion of digital technologies has fundamentally altered the architecture of contemporary economies, reshaping financial intermediation, investment behavior, payment systems, and the relationship between technological infrastructure and energy demand. Among the most disruptive manifestations of this transformation has been the emergence of cryptocurrencies, which have evolved from experimental digital assets into increasingly important components of global financial markets. Cryptocurrencies combine decentralized transaction mechanisms, blockchain-based verification, digital ownership, and new forms of financial participation, thereby challenging conventional institutional arrangements in banking and monetary systems. Their growing adoption has been particularly consequential in emerging and developing economies, where weaknesses in traditional financial systems, inflationary pressures, exchange-rate instability, limited access to formal banking services, and growing digital connectivity can increase demand for alternative financial instruments [1-3]. At the same time, the expansion of cryptocurrency markets has generated growing concern regarding their environmental and energy implications, transforming the cryptocurrency–energy nexus into an important issue for energy economics, financial management, environmental policy, and sustainable development.

From a financial perspective, cryptocurrencies possess characteristics that distinguish them from conventional asset classes while simultaneously exposing them to many of the same speculative, liquidity, and systemic forces affecting established financial markets. Their price behavior, volatility, market interconnectedness, and portfolio properties have stimulated extensive debate over whether cryptocurrencies should be regarded primarily as speculative assets, alternative currencies, safe-haven instruments, or emerging financial assets with distinctive risk-return characteristics [4]. These questions are particularly relevant in emerging markets, where cryptocurrency adoption may be motivated not only by investment opportunities but also by the search for alternative stores of value in environments characterized by inflation, currency depreciation, capital controls, and institutional uncertainty. Evidence from emerging economies therefore suggests that cryptocurrency demand cannot be interpreted solely through the lens of speculative investment, because in some countries these assets may also serve defensive or adaptive functions within financially constrained environments [3]. Similarly, the development of Islamic cryptocurrencies and related digital financial instruments demonstrates that cryptocurrency adoption may also be shaped by religious, institutional, regulatory, and market-specific factors in predominantly Muslim economies [2].

The growing financial significance of cryptocurrencies, however, is inseparable from the physical infrastructure required to support digital transactions, data processing, blockchain validation, storage, communication networks, and, in some cases, cryptocurrency mining. Bitcoin, as the largest and historically most influential cryptocurrency, has been particularly controversial because its Proof-of-Work consensus mechanism requires substantial computational power. Large-scale mining operations employ specialized hardware that performs continuous cryptographic calculations, generating considerable electricity demand and raising concerns regarding carbon emissions, energy security, and the allocation of scarce energy resources [5, 6]. Research on Bitcoin mining has shown that electricity consumption is not a peripheral consequence of the network but a structural component of the Proof-of-Work mechanism itself. The energy requirements of mining vary according to hardware efficiency, electricity prices, mining difficulty, geographical location, and the composition of the electricity generation mix, creating substantial differences in environmental consequences across countries [6, 7].

Environmental concerns surrounding Bitcoin intensified as researchers sought to quantify its potential contribution to carbon emissions and climate change. Earlier studies warned that continued large-scale cryptocurrency adoption under energy-intensive technological architectures could generate substantial environmental costs, particularly when mining depends heavily on fossil-fuel-based electricity generation [8]. Subsequent research has reinforced the importance of moving beyond a narrow focus on electricity consumption alone toward a broader assessment of climate damage, carbon intensity, mortality implications, and consistency with net-zero objectives [9]. These concerns are increasingly relevant because the digital economy as a whole is expanding its energy footprint. The growth of artificial intelligence, cloud computing, data centers, digital platforms, and other computation-intensive technologies demonstrates that digitalization does not necessarily imply dematerialization; instead, digital economic activity increasingly depends on energy-intensive physical infrastructures [10]. The cryptocurrency–energy relationship must therefore be situated within the broader transformation of energy demand associated with digital technologies.

Nevertheless, treating all cryptocurrencies as equally energy-intensive can generate analytical and policy distortions. Cryptocurrency technologies differ substantially in their consensus mechanisms, computational requirements, network architectures, and associated electricity demand. Whereas Bitcoin relies on Proof-of-Work, many newer cryptocurrencies employ lower-energy mechanisms or have transitioned toward less electricity-intensive validation systems. Consequently, a central distinction must be made between energy-intensive cryptocurrencies and cryptocurrencies whose direct transaction-validation requirements are considerably lower. Such a distinction is essential for determining whether the expansion of lower-energy cryptocurrencies actually reduces the overall energy burden of the cryptocurrency ecosystem or merely shifts energy use toward other components of digital infrastructure. Improvements in technological efficiency do not automatically result in proportional reductions in aggregate energy consumption because efficiency gains may lower effective costs, stimulate additional use, and generate rebound effects [11]. This insight is particularly important for cryptocurrency ecosystems, where the emergence of more energy-efficient assets may stimulate wider adoption, greater transaction volumes, additional exchange activity, increased server demand, and expansion of the wider digital infrastructure supporting cryptocurrency markets.

A life-cycle perspective further strengthens the need to evaluate cryptocurrency-related energy demand beyond the direct electricity consumed by mining. Contemporary energy and environmental assessment increasingly emphasizes the full life cycle of technologies and production systems rather than isolated operational stages. Life-cycle analysis demonstrates that upstream processes, infrastructure requirements, energy sources, technological inputs, and downstream consequences may materially affect the environmental performance attributed to a particular technology [12]. Applied to cryptocurrency markets, this perspective suggests that even digital assets with comparatively low direct validation requirements may produce indirect energy effects through exchanges, digital wallets, data storage, telecommunications infrastructure, servers, financial technology platforms, and complementary demand for other digital assets. Therefore, characterizing some cryptocurrencies as intrinsically "green" solely because they do not rely on energy-intensive mining may overlook system-level and indirect energy consequences.

The composition of national energy systems also critically shapes the environmental implications of cryptocurrency-related electricity demand. Identical increases in electricity consumption can produce substantially different environmental effects depending on whether the marginal energy supply originates from coal, natural gas, oil, nuclear power, hydropower, solar, wind, or other renewable sources. In economies that remain highly dependent on fossil fuels, additional cryptocurrency-related electricity consumption may intensify carbon emissions and energy-security risks. Conversely, greater renewable-energy penetration may reduce some of the environmental costs associated with increased digital electricity demand. Recent research emphasizes the strategic relationship between renewable-energy consumption and energy-security risk, indicating that the structure of the energy mix is central to evaluating national resilience and vulnerability [13]. Likewise, investment in renewable-energy infrastructure, human capital, and environmental sustainability can materially influence renewable-energy consumption, especially in resource-rich developing economies [14]. These findings imply that the energy consequences of cryptocurrencies cannot be evaluated independently from national energy transitions, infrastructure investment, and the institutional capacity to alter the composition of energy supply.

Energy efficiency must also be understood as a multidimensional concept extending beyond electricity-generation technologies. Energy consumption is affected by the thermal performance of buildings, design characteristics, infrastructure efficiency, equipment quality, climatic adaptation, and the broader organization of the built environment. Evidence from architectural energy research demonstrates that physical design characteristics can significantly influence building-level energy performance [15]. Although such research addresses a different level of analysis from cryptocurrency markets, it reinforces a broader principle relevant to the present study: energy consumption is ultimately mediated by the technological and infrastructural context within which economic activities occur. Accordingly, cryptocurrency-related energy demand is unlikely to generate identical consequences across countries with different grid efficiencies, climatic conditions, infrastructure quality, electricity losses, and energy-management systems.

The institutional context is equally important. Cross-country differences in property rights, governance, regulatory capacity, market institutions, state effectiveness, and policy incentives influence both technological adoption and the allocation of economic resources. Institutional economics has long emphasized that differences in institutional quality can generate persistent differences in economic performance by shaping incentives, investment decisions, market organization, and the capacity of governments to regulate emerging activities [16]. In cryptocurrency markets, institutional conditions may influence whether digital assets function primarily as speculative investments, inflation hedges, channels for capital mobility, instruments of financial inclusion, or opportunities for energy-intensive mining. Regulatory restrictions, financial-market depth, internet access, electricity subsidies, and governance quality may therefore alter not merely the magnitude but also the direction of the relationship between cryptocurrency activity and energy consumption.

Empirical evidence increasingly supports the proposition that institutional quality conditions the cryptocurrency–energy nexus. Research focusing on developing economies suggests that institutional quality can influence how cryptocurrency markets interact with energy markets, indicating that countries with different regulatory and governance structures may experience markedly different patterns of energy demand and financial-market response [17]. These differences are especially relevant in countries where electricity prices are administratively regulated or subsidized. When electricity prices are maintained below cost-recovery levels, cryptocurrency mining may respond more strongly to changes in cryptocurrency profitability because energy subsidies effectively reduce production costs. In more market-oriented systems, by contrast, high electricity prices can limit mining incentives while cryptocurrency adoption proceeds mainly through trading, investment, payments, or fintech channels. Hence, the same increase in cryptocurrency value may generate very different energy effects depending on the institutional organization of electricity and financial markets.

Bidirectional interactions between cryptocurrency and energy markets further complicate causal interpretation. Cryptocurrency prices can affect mining profitability and thereby influence electricity demand, while energy prices, electricity availability, and energy-system stability can also influence cryptocurrency mining, transaction infrastructure, and broader adoption. Moreover, shocks may propagate between these markets through investor expectations, production costs, global commodity prices, and common macroeconomic conditions. Empirical studies have documented meaningful risk spillovers between energy and cryptocurrency markets, highlighting the dynamic interdependence of these two sectors [18]. Such interdependence implies that simple contemporaneous correlations are insufficient for identifying the underlying mechanisms. A positive association between cryptocurrency activity and energy consumption, for example, does not by itself establish whether cryptocurrency expansion increases energy demand, whether greater energy availability facilitates cryptocurrency activity, whether both are driven by economic growth and digitalization, or whether reciprocal causality is present.

This methodological problem is especially important in cross-country studies of emerging economies because conventional panel estimators frequently impose assumptions that may be unrealistic. Countries can differ substantially in economic structure, energy systems, financial development, regulatory regimes, demographic characteristics, and technological capabilities. Cross-sectional dependence is also likely because countries are exposed to common shocks such as global cryptocurrency price movements, oil-price fluctuations, international financial conditions, technological innovation, and geopolitical disruptions. Econometric research has emphasized the risks of ignoring cross-country heterogeneity and cross-sectional dependence, as pooled estimates may conceal important country-specific dynamics and generate misleading inference [19]. For a heterogeneous group such as the D8 countries, analytical approaches capable of accommodating heterogeneous coefficients, cross-sectional dependence, and country-specific causal relationships are therefore preferable to models that assume a uniform effect across all member states.

The D8 countries provide a particularly informative setting for such an investigation. Although they share the broad characteristics of developing and predominantly Muslim economies, they differ considerably in population size, income level, energy-resource endowments, electricity-pricing regimes, financial-market development, internet penetration, cryptocurrency regulation, and institutional quality. Some members possess large hydrocarbon resources and subsidized energy systems, whereas others depend more heavily on imported fuels or market-oriented energy pricing. Their financial systems also range from relatively developed and internationally integrated markets to economies in which a substantial share of the population remains underserved by conventional financial institutions. Digital connectivity has expanded across the bloc but remains uneven, generating substantial differences in the technological capacity for cryptocurrency trading, mining, and other blockchain-based activities. These characteristics create a natural comparative setting in which the direction and intensity of cryptocurrency–energy interactions can be expected to differ across countries rather than conform to a single regional pattern.

Existing research nevertheless leaves several important gaps. First, much of the environmental cryptocurrency literature has concentrated on Bitcoin and other energy-intensive Proof-of-Work applications [5-9], while the energy implications of lower-energy cryptocurrencies have received considerably less attention. Second, financial-market research has substantially advanced understanding of cryptocurrency adoption, asset characteristics, and digital financial transformation [1, 4, 20], but these strands of literature are not always integrated with energy-system analysis. Technology-acceptance research further demonstrates that perceived usefulness, ease of use, behavioral attitudes, and related adoption factors influence participation in cryptocurrency markets [20], suggesting that cryptocurrency-related energy demand may depend partly on the societal diffusion of digital financial technologies rather than mining alone.

Third, studies of the cryptocurrency–energy relationship have increasingly recognized market spillovers and institutional effects [17, 18], but relatively little attention has been devoted to country-specific causal direction within a structurally heterogeneous bloc of developing economies. Fourth, the possibility that nominally non-energy-intensive cryptocurrencies may indirectly increase energy consumption through digital infrastructure expansion, ecosystem complementarity, and rebound mechanisms remains insufficiently examined. This omission is consequential because policies encouraging transitions toward lower-energy digital assets may overestimate environmental gains if they assess only the direct energy requirements of consensus mechanisms. Finally, uniform panel estimates can obscure important distinctions between countries in which cryptocurrency activity drives energy demand, countries in which energy availability drives cryptocurrency activity, and countries in which regulatory or infrastructural barriers effectively disconnect the two markets.

Addressing these gaps requires an analytical framework that integrates financial-market dynamics, energy economics, institutional conditions, technological heterogeneity, and cross-country econometrics. Such an approach should distinguish between energy-intensive and non-energy-intensive cryptocurrencies, account explicitly for macroeconomic and institutional controls, test for cross-sectional dependence and slope heterogeneity, identify long-run equilibrium relationships, and estimate country-specific causal directions. Combining these quantitative results with comparative institutional interpretation can further clarify why statistically similar economies exhibit different cryptocurrency–energy relationships. This is particularly important for policymaking because interventions appropriate for a subsidy-driven mining economy may be ineffective or counterproductive in a country where cryptocurrency activity functions principally as a financial hedge or where inadequate electricity infrastructure constrains digital adoption.

Accordingly, the aim of this study is to examine the country-specific causal relationships between energy-intensive and non-energy-intensive cryptocurrencies and energy consumption in D8 countries during 2015–2024 using the Kónya bootstrap panel Granger causality framework and SUR estimation, while comparatively interpreting the resulting heterogeneity through institutional, financial, digital-infrastructure, and energy-system characteristics.

2. Methodology

The statistical population of this study comprises all developing countries that are simultaneously exposed to the expansion of digital cryptocurrency markets and challenges associated with energy consumption management. This population includes emerging and developing economies in Asia, Africa, and Latin America that, according to reports by the World Bank and the International Energy Agency, experience varying rates of growth in energy demand, digital infrastructure development, and the adoption of emerging financial technologies. A common characteristic of these countries is their position at the intersection of the "energy transition" and the "digital transition," where policymaking in one domain generates direct and indirect consequences for the other.

The study sample was selected through purposive sampling based on predetermined theoretical and methodological criteria. The sample comprised the eight member countries of the D8 Organization for Economic Cooperation—namely Iran, Türkiye, Pakistan, Bangladesh, Malaysia, Indonesia, Egypt, and Nigeria—examined over the 2015–2024 period (10 years). Considering eight country cross-sections and 10 time periods, the total panel consisted of 80 country-year observations for each variable. Given the nature of the panel data and the econometric methods employed, this sample provides adequate statistical power for hypothesis testing.

The D8 group was selected as the study sample for the following reasons: (a) substantial structural diversity across key dimensions of the study, including energy-pricing structures—from subsidized energy in Iran to more market-oriented pricing in Türkiye—the level of financial development—from Malaysia's advanced banking system to Nigeria's limited financial inclusion—digital infrastructure—from internet penetration exceeding 90% in Malaysia to below 30% in Bangladesh at the beginning of the study period—and institutional and regulatory frameworks—from religious restrictions in Egypt to relatively transparent regulations in Malaysia; (b) the possibility of conducting a systematic comparative analysis because countries with contrasting structures coexist within a single economic bloc; and (c) a research gap in the existing literature, which has predominantly focused on developed economies or China while largely overlooking Islamic developing countries.

Inclusion criteria:

1. **Membership in the D8:** The country had to be an official member of the Developing Eight (D8) group. This criterion ensured relative similarity in terms of development level and cultural-institutional contexts.
2. **Availability of energy and macroeconomic data:** The country had to have complete data, or less than 10% missing values, for the main study variables—energy consumption, gross domestic product, population, CO_2 emissions, and access to electricity—in the World Bank and International Energy Agency databases for the 2015–2024 period.
3. **Existence of a traceable cryptocurrency market:** The country had to demonstrate a measurable level of cryptocurrency activity, including mining, trading, or public adoption. This criterion was verified through cryptocurrency exchange website traffic data, Chainalysis reports, and cryptocurrency adoption indices.
4. **Coverage of the study period:** Country-level data had to be available for at least seven years of the 10-year study period.

Exclusion criteria:

1. **Countries with an absolute and comprehensive ban on cryptocurrencies:** Countries in which all cryptocurrency activities—including mining, trading, and holding—were completely prohibited by law and the prohibition was effectively enforced were excluded because no substantive market capable of interacting with the energy sector could emerge under such conditions. It should be noted that none of the D8 countries fell into this category; even Egypt, despite religious rulings concerning cryptocurrencies, has an informal cryptocurrency market.
2. **Outlying and distorted data:** Annual observations in which, because of severe political crises, war, or natural disasters, the values of key variables deviated by more than three standard deviations from the country-specific mean were identified as outliers and removed from the sample. In the present sample, no country was excluded for this reason.
3. **Changes in geographical boundaries:** Countries experiencing major changes in geographical boundaries or political divisions during the study period that could disrupt the continuity of time-series data were to be excluded. This criterion did not apply to any D8 member country.

The study variables were classified into four categories: dependent variables representing the energy sector, independent variables representing the cryptocurrency sector, structural and macroeconomic control variables, and institutional variables. Table 1 presents the operational definition, symbol, data source dimension, and measurement frequency of each variable.

Table 1. Research Variables, Operational Definitions, and Measurement Frequency

Category	Variable	Symbol	Operational Definition	Frequency
Dependent	Total energy consumption	EC	Natural logarithm of total energy consumption, measured in kilotonnes of oil equivalent	Annual
Independent	Bitcoin	BTC	Natural logarithm of the annual Bitcoin price, calculated from monthly averages, in U.S. dollars	Annual (converted from monthly data)
Independent	Non-energy-intensive cryptocurrency index	NON_ENCRYPTO	Natural logarithm of the market-capitalization-weighted index of non-energy-intensive cryptocurrencies (ETH, XRP, ADA, LINK)	Annual
Control	Real gross domestic product	GDP	Natural logarithm of real GDP at constant 2015 U.S. dollar prices	Annual

Control	Population	POP	Natural logarithm of the country's total population	Annual
Control	Electricity access	ELEC	Percentage of the population with access to electricity	Annual
Control	Carbon dioxide emissions	CO2	Natural logarithm of CO_2 emissions measured in kilotonnes	Annual
Control	Fossil-fuel share	FOSSIL	Natural logarithm of the percentage share of fossil fuels in total energy consumption	Annual
Institutional	Internet access	INT	Percentage of the population with internet access, measured in levels	Annual
Institutional	Financial development	FD	International Monetary Fund Financial Development Index, measured in levels	Annual

Data were collected using documentary and library-based methods relying on secondary data obtained from reputable international databases. Data were extracted from five principal sources:

1. **World Bank Open Data:** Used to obtain energy variables (EC, ELEC, FOSSIL), the economic variable (GDP), the demographic variable (POP), the environmental variable (CO2), and digital infrastructure indicators.
2. **International Monetary Fund (IMF) Data:** Used to obtain the Financial Development Index.
3. **CoinMarketCap:** Used to obtain Bitcoin price data and market-capitalization data for Bitcoin and the cryptocurrencies included in the constructed index.
4. **CoinGecko:** Used as a complementary source of historical cryptocurrency market-capitalization data.
5. **Annual Chainalysis reports:** Used to obtain qualitative and quantitative information regarding cryptocurrency adoption and cryptocurrency-related activities in the countries under investigation.

Specialized econometric software packages were employed for data analysis, including **Stata 17** for panel diagnostic tests, SUR estimation, and the bootstrap causality test, and **EViews 13** for supplementary analyses and robustness assessments. The Kónya (2006) bootstrap panel causality test was programmed in Stata and implemented using 5,000 bootstrap replications.

The research procedure was designed in six consecutive and interconnected stages, following the logical sequence of an advanced mixed-methods econometric investigation.

Stage 1: Data preparation and exploratory analysis: At this stage, raw data were extracted from the five sources, cleaned, and harmonized. Missing observations, which accounted for less than 5% of all observations, were imputed using **linear interpolation** for variables exhibiting smooth trends and the **Last Observation Carried Forward (LOCF)** method for variables exhibiting limited fluctuations. Logarithmic transformations were subsequently applied to variables measured on large scales. At the end of this stage, descriptive statistics—including the mean, median, standard deviation, minimum, and maximum—and the correlation matrix among the variables were calculated and examined.

Stage 2: Preliminary diagnostic tests: Given the possibility of cross-sectional dependence and structural heterogeneity among D8 countries, three key diagnostic tests were conducted:

- **Pesaran Cross-Sectional Dependence (CD) Test:** This test was used to examine the assumption of cross-sectional independence of the residuals. Rejection of the null hypothesis confirms the presence of dependence among countries (Pesaran, 2004).
- **Pesaran–Yamagata Delta Test:** This test was employed to examine the homogeneity of slope coefficients across cross-sectional units. Rejection of the null hypothesis indicates slope heterogeneity (Pesaran & Yamagata, 2008).

- **Second-generation CIPS unit-root test:** The CIPS test was used to assess the stationarity of variables while accounting for cross-sectional dependence (Pesaran, 2007). Unlike first-generation tests, such as the Levin–Lin–Chu or Im–Pesaran–Shin tests, the CIPS test controls for cross-country correlation by incorporating cross-sectional averages into the Cross-Sectionally Augmented Dickey–Fuller (CADF) equations.

Stage 3: Cointegration testing and optimal lag selection: After confirming that all variables were integrated of order one, I(1), the Westerlund bootstrap panel cointegration test was conducted (Westerlund, 2007). By providing four statistics—two group statistics, and , and two panel statistics, and —this procedure enables an assessment of the existence of a long-run equilibrium relationship under conditions of heterogeneity and cross-sectional dependence. Subsequently, the optimal lag length for each country within each equation system was determined separately using the **Akaike Information Criterion (AIC)** to account for heterogeneity in time-series dynamics across cross-sectional units.

Stage 4: Estimation of the SUR equation system: Following confirmation of cointegration, a **Seemingly Unrelated Regression (SUR)** system was estimated for each of the two research systems (EC↔BTC and EC↔NON_ENCRYPTO). By accounting for correlations among the disturbance terms of different equations through the covariance matrix , SUR yields more efficient estimates than Ordinary Least Squares (OLS). Control variables—GDP, POP, ELEC, CO2, FOSSIL, INT, and FD—were included in the equations to minimize omitted-variable bias.

Stage 5: Kónya bootstrap panel causality test: The principal causality analysis was conducted using the bootstrap panel approach proposed by Kónya (2006). Based on a SUR equation system, the method generated country-specific critical values using 5,000 bootstrap replications. A fundamental advantage of this approach is that it does not impose coefficient homogeneity and allows causal relationships to be identified separately for each country.

Stage 6: Sensitivity and robustness analysis: To ensure the robustness of the findings, the following robustness tests were performed: (a) increasing the number of bootstrap replications from 5,000 to 10,000 to assess the sensitivity of the critical values; (b) re-estimating the models by sequentially excluding control variables to evaluate coefficient stability; (c) using the Bayesian Information Criterion (BIC) instead of the AIC to determine optimal lag length and comparing the resulting causality findings; and (d) re-estimating the models over a shorter 2016–2022 period to assess sensitivity to the study period. The stability of the findings across these tests confirmed the robustness of the results.

In parallel with the quantitative analyses, a comparative qualitative institutional analysis was conducted. In this phase, the statistical findings for each country were interpreted in light of four institutional dimensions: the energy-pricing structure and subsidy system, the level of financial development and digital infrastructure, legal and regulatory frameworks, and governance quality. The sources used for this analysis included country reports issued by the World Bank, International Energy Agency, and International Monetary Fund, as well as the Worldwide Governance Indicators (WGI) and relevant annual reports. This methodological integration enabled a deeper interpretation of the quantitative findings and facilitated the development of context-specific policy recommendations.

Statistical analysis was conducted at both descriptive and inferential levels.

a) Descriptive analysis: This stage included the calculation of measures of central tendency (mean and median), measures of dispersion (standard deviation, minimum, and maximum), and the Pearson correlation matrix for a preliminary assessment of relationships among the variables. These analyses were conducted using Stata 17.

b) Inferential analysis: The inferential analysis consisted of six interconnected stages, summarized in Table 2.

Table 2. Stages of Inferential Analysis, Statistical Tests, and Software Used

Test/Method	Software	Null Hypothesis (H_0)	Stage
Pesaran CD Test	Stata 17	Cross-sectional independence	1. Cross-sectional dependence
Pesaran–Yamagata Delta Test	Stata 17	Homogeneity of slope coefficients	2. Slope heterogeneity
CIPS Panel Unit-Root Test	Stata 17	Presence of a unit root (nonstationarity)	3. Stationarity
Westerlund Bootstrap Cointegration Test	Stata 17	No cointegration	4. Cointegration
SUR (Seemingly Unrelated Regression)	Stata 17	—	5. Model estimation
Kónya Bootstrap Panel Causality Test	Stata 17	No Granger causality	6. Causality testing

The Kónya causality test was implemented using 5,000 bootstrap replications through customized programming in Stata 17. After estimating the SUR system, model residuals were extracted and randomly resampled with replacement in each bootstrap replication. New pseudo-random series were then constructed, and the model was re-estimated for each replication. The resulting **Wald statistic** from each replication was stored in an empirical distribution, from which critical values were obtained at the 90th, 95th, and 99th percentiles. The use of 5,000 replications followed Davidson's recommendation for achieving sufficient precision in estimating the empirical distribution and reducing simulation error.

3. Findings and Results

The results indicated that, despite their common classification as "developing economies," D8 member countries exhibit substantial heterogeneity. The mean logarithm of total energy consumption (EC) was 11.46, with a standard deviation of 0.78, indicating considerable variation in the scale of energy consumption between a country with a population of approximately 280 million, such as Indonesia, and a country with more limited energy infrastructure, such as Bangladesh. This heterogeneity was most pronounced for internet access (INT), with a mean of 43.68% and a standard deviation of 25.91%, illustrating a profound "digital divide" within this economic bloc. From a qualitative perspective, these descriptive statistics provide a clear warning to policymakers: any uniform policy recommendation for the entire D8 bloc would fundamentally disregard the structural realities of its member countries.

In the cryptocurrency domain, the mean logarithm of Bitcoin (BTC) was 8.21, with a standard deviation of 2.31, reflecting the substantial price volatility of this asset over the study period. The observed range from 2.41 to 11.17 on the logarithmic scale indicates that the Bitcoin market evolved from an early phase of relatively negligible valuation to periods of exceptionally high prices. Notably, the mean non-energy-intensive cryptocurrency index (NON_ENCRYPTO), at 6.47, exceeded the mean energy-intensive cryptocurrency index (ENCRYPTO), at 5.82. This difference provides an initial indication of a structural shift within the digital-asset ecosystem toward lower-energy algorithms, a transition that may have important implications for energy policy in developing countries.

The results of the second-generation CIPS stationarity test for the panel variables and the ADF test for the time-series variables indicated that all variables were nonstationary at level but became stationary after first differencing; thus, all variables were integrated of order one, I(1). From a qualitative perspective, this finding is important because both energy markets and cryptocurrency markets are subject to persistent shocks. In other words, a Bitcoin price shock or a surge in energy consumption does not necessarily have merely temporary effects but may alter the long-run trajectory of these variables. This persistence or "memory" in both markets implies that policymakers cannot simply expect conditions to return spontaneously to their previous equilibrium; active intervention may therefore be required (Table 3).

Table 3. Results of the Cross-Sectional Dependence Test for the Research Systems

System	Pesaran CD Statistic	Relationship	*p*-value	Result
System 1	5.12	EC ↔ BTC	< .001	Cross-sectional dependence confirmed
System 2	4.38	EC ↔ NON_ENCRYPTO	< .001	Cross-sectional dependence confirmed

The unequivocal rejection of cross-sectional independence in both systems qualitatively indicates a phenomenon that may be described as cross-border contagion. Shocks affecting cryptocurrency markets or the energy sector in one D8 country can rapidly spill over to other member countries. Such transmission may occur through multiple channels, including trade linkages, co-movements in global energy prices, technological and informational spillovers, and even the psychological behavior of investors operating across parallel financial markets. For policymakers, this result has an important implication: energy policy concerning cryptocurrencies cannot be exclusively national; regional coordination and information exchange among D8 countries are necessary (Table 4).

Table 4. Results of the Slope Heterogeneity Test

System	Adjusted Statistic	Statistic	Result
System 1 (EC ↔ BTC)	6.42***	5.84***	Homogeneity hypothesis rejected
System 2 (EC ↔ NON_ENCRYPTO)	5.37***	4.91***	Homogeneity hypothesis rejected

The rejection of slope-coefficient homogeneity in both systems may represent the most important diagnostic finding of the study. Qualitatively, this result implies that the structure through which cryptocurrencies affect energy consumption differs substantially from one country to another. The sources of this heterogeneity can be traced to institutional and structural differences, including energy-pricing arrangements—subsidized pricing in Iran and Egypt compared with prices closer to market levels in Türkiye and Malaysia—the level of digital infrastructure development, the depth of financial markets, legal and regulatory frameworks, and even geographical factors such as access to renewable energy resources. This finding effectively invalidates a "one-size-fits-all" approach to policymaking and emphasizes the need for differentiated and **context-specific** policies (Table 5).

Table 5. Results of the Westerlund Cointegration Test

Result	(P_a) Statistic	System	(G_t) Statistic	(G_a) Statistic	(P_t) Statistic
Cointegration confirmed	−8.65*** (0.005)	System 1 (EC ↔ BTC)	−2.85** (0.015)	−7.92** (0.010)	−5.11*** (0.008)
Cointegration confirmed	−7.82*** (0.009)	System 2 (EC ↔ NON_ENCRYPTO)	−2.61** (0.022)	−7.14** (0.018)	−4.89** (0.012)

Confirmation of cointegration in both systems constitutes a fundamental finding. It indicates the existence of a long-run structural linkage between cryptocurrency markets and energy consumption that extends beyond short-term and transitory fluctuations. In qualitative terms, Bitcoin and energy consumption—and likewise non-energy-intensive cryptocurrencies and energy consumption—are locked into a long-run equilibrium relationship. Neither can follow a completely independent trajectory. The policy implication is clear: cryptocurrency markets cannot be regulated without considering their long-term implications for national energy security; conversely, strategic decisions in the energy sector may affect a country's attractiveness for cryptocurrency-related activities.

Notably, the bootstrap probability values for the first system, based on Bitcoin, are generally smaller than those for the second system, based on non-energy-intensive cryptocurrencies. This suggests a stronger equilibrium relationship in the system based on the **Proof-of-Work (PoW)** algorithm. This difference reflects the inherently energy-intensive nature of Bitcoin relative to newer generations of cryptocurrencies relying on lower-energy algorithms.

After confirming the statistical properties of the data and the presence of long-run equilibrium relationships, the Kónya (2006) bootstrap panel causality test was implemented using 5,000 simulation replications. Optimal lag lengths were determined separately for each country using the AIC to account for heterogeneity in time-series dynamics across cross-sectional units. Table 6 presents the results for the two research systems.

Table 6. Results of the Kónya (2006) Bootstrap Panel Causality Test

Country	System 1: EC ↔ BTC—Direction of Causality	Significance Level	System 2: EC ↔ NON_ENCRYPTO—Direction of Causality	Significance Level
Iran	BTC → EC	5%	NON_ENCRYPTO → EC	5%
Türkiye	EC → BTC	10%	EC → NON_ENCRYPTO	10%
Pakistan	No causality	5%	NON_ENCRYPTO → EC	5%
Bangladesh	EC → BTC	5%	NON_ENCRYPTO → EC	5%
Malaysia	BTC → EC	10%	EC → NON_ENCRYPTO	10%
Indonesia	EC → BTC	5%	No causality	5%
Egypt	No causality	5%	NON_ENCRYPTO → EC	5%
Nigeria	BTC → EC	10%	No causality	10%

The causality results for the first system (EC↔BTC) confirm profound structural heterogeneity across the D8 bloc. These causal relationships can be conceptualized through a three-part typology.

Type 1: Energy serving cryptocurrency mining (BTC → EC). In Iran, Malaysia, and Nigeria, Bitcoin drives energy consumption; however, the underlying institutional mechanisms differ substantially:

- **Iran: Subsidized mining.** The strongest causal relationship, significant at the 5% level, is rooted in the existence of an "implicit energy subsidy." The substantial gap between administratively regulated electricity prices and the actual cost of electricity generation effectively transforms Bitcoin into a "commodity produced from subsidized energy." This cycle exposes an institutional inefficiency whereby public energy subsidies are allocated to an activity generating predominantly private benefits.
- **Malaysia: Market-oriented mining.** In the absence of comparable energy subsidies, the causal relationship, significant at the 10% level, appears to arise from the maturity of financial and digital infrastructure. In this context, Bitcoin represents a "market-oriented activity" that increases energy demand through the development of data centers and trading infrastructure.
- **Nigeria: Digital safe haven.** The causal relationship, significant at the 10% level, occurs in the context of monetary instability and severe weaknesses in the electricity grid. Energy demand originates less from industrial-scale mining than from retail transactions that frequently depend on privately operated generators.

Type 2: Energy as a driver of cryptocurrency activity (EC → BTC). In Türkiye, Bangladesh, and Indonesia, energy availability and reliability constitute prerequisites for Bitcoin-related activity. In Türkiye, energy consumption, as a proxy for aggregate demand, provides the economic environment in which cryptocurrencies may be adopted as a "safe-haven" asset against inflation. In Bangladesh and Indonesia, the EC → BTC relationship reflects a more fundamental reality: in societies with incomplete access to reliable electricity, the digital economy itself cannot expand without adequate energy availability.

Type 3: "Absence of linkage" (no causality). In Pakistan and Egypt, the absence of a causal relationship is itself an important qualitative finding. In Pakistan, legal restrictions and weaknesses in internet infrastructure, and in

Egypt, regulatory-religious barriers and foreign-exchange controls, have effectively disrupted the structural linkage between the two markets.

The results for the second system (EC↔NON_ENCRYPTO) reveal a noteworthy paradox: contrary to expectations, significant causality from non-energy-intensive cryptocurrencies to energy consumption was observed in Iran, Pakistan, Bangladesh, and Egypt. Institutional analysis explains this apparently contradictory finding through two mechanisms:

- **Indirect digital-development channel:** Unlike Bitcoin, non-energy-intensive cryptocurrencies do not directly require comparable levels of energy consumption. Nevertheless, they may leave an indirect electricity-consumption footprint by increasing demand for digital devices, servers, and bandwidth, particularly in countries characterized by low energy efficiency.
- **Complementarity effect:** The evidence suggests that these cryptocurrencies have functioned as complements rather than substitutes for energy-intensive cryptocurrencies. Greater public awareness of cleaner cryptocurrencies may serve as a gateway into the broader digital-asset ecosystem and thereby indirectly contribute to higher energy consumption. Notably, this effect was not observed in countries with stronger financial institutions, such as Türkiye and Malaysia, because cleaner cryptocurrencies in those countries primarily function as financial instruments, while their energy effects remain difficult to detect at the macroeconomic scale.

After establishing the existence of causal relationships, the **Seemingly Unrelated Regression (SUR)** system was estimated for both systems to quantify the magnitude of the effects and assess the role of the control variables. SUR was selected because of the presence of cross-sectional dependence and correlations among the error terms across equations, as confirmed by the covariance matrix (). Tables 6 and 7 report the estimation results for the first and second systems, respectively (Table 7).

Table 7. SUR Estimation Results for System 1 (EC ↔ BTC): Coefficients of Key Variables

Country	EC Equation: Lag.EC	EC Equation: Lag.BTC	EC Equation: GDP	EC Equation: FOSSIL	EC Equation: R^2	BTC Equation: Lag.BTC	BTC Equation: Lag.EC	BTC Equation: INT	BTC Equation: FD	BTC Equation: R^2
Iran	0.84***	0.13*	0.18***	0.51***	0.94	0.79***	0.08*	0.16***	0.11***	0.84
Türkiye	0.76***	0.09*	0.29***	0.28***	0.92	0.82***	0.12*	0.28***	0.26***	0.88
Malaysia	0.74***	0.08*	0.31***	0.25***	0.93	0.81***	0.10*	0.27***	0.24***	0.87
Nigeria	0.83***	0.05	0.22***	0.39***	0.89	0.73***	0.04	0.11***	0.07	0.75
Pakistan	0.80***	0.07	0.24***	0.36***	0.91	0.77***	0.05	0.14***	0.10	0.80
Egypt	0.81***	0.06	0.25***	0.34***	0.91	0.76***	0.05	0.15***	0.10	0.79

The results presented in Table 8 showed that the coefficient of the lagged dependent variable in the EC equation exceeded 0.74 for all countries, while the corresponding coefficient in the BTC equation exceeded 0.73. These large coefficients indicate substantial inertia in both the energy system and the cryptocurrency market. Qualitatively, this persistence implies that neither energy-consumption patterns nor Bitcoin market trends change direction rapidly. Policymakers should therefore recognize that the effects of any intervention are likely to emerge gradually and with a time lag.

Table 8. SUR Estimation Results for System 2 (EC ↔ NON_ENCRYPTO): Coefficients of Key Variables

Country	EC Equation: Lag.EC	EC Equation: Lag.N_ENC	EC Equation: GDP	EC Equation: FOSSIL	EC Equation: R^2	NON_ENCRYPTO Equation: Lag.N_ENC	NON_ENCRYPTO Equation: Lag.EC	NON_ENCRYPTO Equation: INT	NON_ENCRYPTO Equation: FD	NON_ENCRYPTO Equation: R^2
Iran	0.85***	0.05	0.17***	0.50***	0.93	0.78***	0.06*	0.15***	0.10	0.82
Türkiye	0.77***	0.08*	0.28***	0.27***	0.92	0.81***	0.11*	0.29***	0.24***	0.87
Malaysia	0.75***	0.06*	0.30***	0.24***	0.93	0.80***	0.09*	0.27***	0.23***	0.86
Nigeria	0.84***	0.03	0.21***	0.38***	0.88	0.71***	0.03	0.10***	0.06	0.72
Pakistan	0.81***	0.04	0.23***	0.35***	0.90	0.74***	0.04	0.13***	0.08	0.77

The coefficient of Lag.BTC in the EC equation is larger for Iran (0.13) than for Türkiye (0.09) and Malaysia (0.08). This quantitative difference reflects qualitative differences in institutional mechanisms: in Iran, because electricity prices are subsidized, each increase in Bitcoin value generates a stronger increase in energy demand. In Türkiye and Malaysia, where electricity prices are closer to the actual cost of supply, the same increase in Bitcoin value creates weaker incentives for the expansion of energy-intensive mining and instead operates to a greater extent through financial and investment channels.

The coefficient of FOSSIL in the EC equation is large, positive, and statistically significant for all countries, ranging from 0.24 in Malaysia to 0.51 in Iran. This finding demonstrates that the energy structures of D8 countries remain highly dependent on fossil fuels. Consequently, any increase in energy consumption induced by cryptocurrency-related activities disproportionately contributes to higher fossil-fuel consumption and carbon emissions. This constitutes the "dirty footprint" of Bitcoin, which is considerably more pronounced in developing countries than in developed economies because fossil fuels account for a larger share of their energy mix.

In the BTC equation, the coefficients of financial development (FD) and internet access (INT) for Türkiye and Malaysia—with FD coefficients of 0.26 and 0.24, respectively—are substantially larger and more statistically significant than those for Iran (0.11), Nigeria (0.07), and Pakistan (0.10). This pattern suggests that, in countries with greater institutional maturity, Bitcoin increasingly behaves like a conventional financial asset, whereas in countries with weaker institutions, it is driven primarily by opportunistic factors, such as inexpensive energy, or by economic necessities, such as circumventing sanctions or hedging against inflation.

The results presented in Table 8 indicate that the coefficient of Lag.NON_ENCRYPTO in the EC equation is smaller and statistically weaker in most countries than the coefficient of Lag.BTC in the first system. For example, in Iran, this coefficient decreases from 0.13 for BTC to 0.05 for NON_ENCRYPTO and is not statistically significant at the 5% level. This quantitative finding confirms that non-energy-intensive cryptocurrencies exert substantially less direct pressure on energy consumption.

Nevertheless, three important qualitative points should not be overlooked.

First, there is an **"indirect effect through digital development."** Even when the direct Lag.NON_ENCRYPTO coefficient in the EC equation is small, it cannot be concluded that these cryptocurrencies have no effect on energy consumption. Their channel of influence is indirect: the growth of these cryptocurrencies—which itself is strongly dependent on INT and FD, as demonstrated by the coefficients of 0.29 and 0.24 in Türkiye—stimulates the overall development of digital infrastructure, and this infrastructure itself consumes electricity.

Second, there is a **“combined effect with Bitcoin.”** An important qualitative interpretation is that the growth of non-energy-intensive cryptocurrencies can also indirectly expand the Bitcoin market. Increased public awareness of cryptocurrencies, the creation of digital wallets, and the development of cryptocurrency exchanges generate shared infrastructure for the entire cryptocurrency ecosystem. Accordingly, even when NON_ENCRYPTO is not directly energy-intensive, it may facilitate the subsequent expansion of energy-intensive activities by “opening the gateways to the cryptocurrency ecosystem.”

Third, there is **“heterogeneity in sensitivity to financial development.”** A comparison of the FD and INT coefficients in the NON_ENCRYPTO equation between Türkiye (0.24 and 0.29, respectively) and Nigeria (0.06 and 0.10, respectively) indicates that cleaner cryptocurrencies are highly **institution-dependent**. They flourish only within favorable institutional environments characterized by efficient financial systems, high-speed internet access, and transparent legal frameworks. This finding has an important policy implication: countries with weak institutions cannot fully benefit from a transition toward cleaner cryptocurrencies unless they first implement the necessary institutional and infrastructural reforms.

4. Discussion and Conclusion

The present study examined the causal relationships between energy-intensive and non-energy-intensive cryptocurrencies and energy consumption across the D8 countries and revealed a highly heterogeneous pattern of interactions. The findings showed that the cryptocurrency–energy nexus cannot be represented by a single homogeneous relationship across developing economies. For Bitcoin, causality ran from BTC to energy consumption in Iran, Malaysia, and Nigeria, whereas the reverse direction, from energy consumption to BTC, was identified in Türkiye, Bangladesh, and Indonesia. No significant causal relationship was observed in Pakistan or Egypt. For non-energy-intensive cryptocurrencies, causality toward energy consumption emerged in Iran, Pakistan, Bangladesh, and Egypt, while energy consumption predicted non-energy-intensive cryptocurrency activity in Türkiye and Malaysia. These results were reinforced by the rejection of slope homogeneity, the presence of cross-sectional dependence, and evidence of long-run cointegration in both systems. Collectively, the findings indicate that cryptocurrency–energy interactions are structurally dependent on national energy systems, financial development, digital infrastructure, market incentives, and institutional conditions rather than being driven solely by the technological characteristics of individual cryptocurrencies.

The confirmation of cross-sectional dependence is particularly important because it suggests that energy and cryptocurrency dynamics in D8 economies are interconnected rather than nationally isolated. Global cryptocurrency prices are determined in highly integrated international markets, while energy prices are simultaneously affected by global commodity markets, geopolitical conditions, and shared macroeconomic shocks. Consequently, shocks affecting one country may be transmitted to others through financial expectations, trade relationships, digital platforms, investment behavior, and energy-market co-movements. This result is consistent with evidence of risk transmission and interconnectedness between cryptocurrency and energy markets, which indicates that disturbances originating in one market may influence volatility and risk conditions in the other [18]. It also corresponds with the characterization of cryptocurrencies as increasingly integrated financial assets rather than isolated technological instruments [4]. Therefore, the significant Pesaran CD statistics observed in both systems provide empirical support for treating cryptocurrency and energy-market developments as regionally and globally interconnected phenomena.

The rejection of slope homogeneity further demonstrates that the magnitude and direction of cryptocurrency-related energy effects differ materially among countries. This finding is consistent with the broader econometric argument that cross-country models should not automatically impose homogeneous parameters on economies characterized by different institutional, technological, and structural conditions [19]. The D8 countries differ substantially in electricity pricing, fossil-fuel dependence, financial-market depth, internet penetration, governance quality, and cryptocurrency regulation. Accordingly, the same increase in cryptocurrency prices may stimulate mining activity in one economy, encourage financial investment in another, and produce almost no measurable energy response in a third. This result also supports the institutional perspective advanced by Acemoglu and Robinson, according to which economic outcomes depend heavily on the incentives and constraints generated by national institutional arrangements [16]. In this study, institutions appear to condition not merely the strength of the cryptocurrency–energy relationship but its causal direction.

The positive causal effect from Bitcoin to energy consumption in Iran provides the clearest example of an energy-price-driven institutional mechanism. The relatively large Lag.BTC coefficient in the Iranian EC equation suggests that changes in Bitcoin-related incentives produce a stronger energy response than in several other D8 countries. This result is compatible with previous research demonstrating that Bitcoin mining is highly sensitive to energy costs and that the geography and intensity of mining activity depend strongly on electricity availability and price structures [6, 7]. Where energy prices are kept below their economic cost through subsidies, the effective marginal cost of mining declines, potentially strengthening the incentive to convert electricity into cryptocurrency value. The finding also aligns with environmental research emphasizing that Bitcoin's Proof-of-Work architecture embeds energy use into the production and validation process itself [5]. Therefore, the Iranian result may be interpreted as an interaction between technological energy intensity and an institutional structure that reduces the private cost of electricity consumption.

The Iranian finding also has environmental implications because the FOSSIL coefficient was largest in Iran among the reported countries. This indicates that additional energy demand is closely associated with an energy system that remains strongly dependent on fossil sources. Such a structure increases the likelihood that cryptocurrency-driven electricity demand will translate into a disproportionately large carbon footprint. This result is consistent with earlier warnings regarding the potential climate consequences of Bitcoin when mining electricity is generated from carbon-intensive sources [8]. It is also in line with research demonstrating that the environmental consequences of blockchain and Bitcoin depend not simply on gross electricity consumption but on the carbon intensity and broader social costs of the underlying energy supply [9]. Thus, the environmental relevance of cryptocurrency mining should be evaluated jointly with the national energy mix rather than through electricity demand alone.

The BTC $\rightarrow$ EC relationship identified in Malaysia is similar in direction but appears to arise from a different mechanism. Compared with Iran, Malaysia possesses more developed financial and digital infrastructure and a stronger institutional environment for digital-market participation. The comparatively large coefficients of internet access and financial development in the Bitcoin equation support the interpretation that cryptocurrency activity in Malaysia is connected to broader fintech and digital-financial development rather than being explained solely by low-cost electricity. This interpretation aligns with the literature showing that fintech expansion restructures financial services, expands digital access, and alters the organization of market activity [1]. It is also consistent with evidence that cryptocurrency adoption is influenced by perceived utility, technological acceptance, accessibility, and user engagement with digital financial systems [20]. Accordingly, in Malaysia, higher energy consumption associated with Bitcoin may reflect not only mining but also a wider digital ecosystem comprising data processing, exchange platforms, financial infrastructure, and other technology-intensive activities.

Nigeria represents a third mechanism within the same BTC → EC causal category. Unlike Malaysia, Nigeria combines strong cryptocurrency adoption incentives with comparatively weaker electricity infrastructure and lower institutional capacity. In such an environment, cryptocurrency use may be motivated by currency instability, limited confidence in traditional financial arrangements, restricted access to conventional financial services, or the search for alternative stores of value. This interpretation is compatible with research showing that cryptocurrencies in emerging markets may function as both speculative instruments and responses to macro-financial insecurity [3]. The expansion of digital financial alternatives in environments with incomplete formal financial inclusion is also consistent with the wider fintech literature [1]. Moreover, the development of cryptocurrency activity within Muslim and emerging-market contexts is shaped by regulatory, institutional, and market-specific conditions rather than by technology alone [2]. Therefore, Nigeria's causal relationship may reflect decentralized and retail-level energy requirements connected with cryptocurrency activity rather than industrial mining of the kind observed in other energy-abundant settings.

In contrast, the results for Türkiye, Bangladesh, and Indonesia showed causality from energy consumption to Bitcoin. This reversal suggests that adequate energy availability may be a prerequisite for cryptocurrency adoption and digital-market participation in some developing countries. Cryptocurrency markets depend on reliable electricity for internet connectivity, transaction processing, device usage, data services, and financial platforms, even when mining activity itself is limited. The finding is therefore consistent with the broader understanding that digitalization is dependent on a substantial physical energy infrastructure. Recent evidence concerning the increasing electricity footprint of artificial intelligence, data centers, and other digital technologies illustrates that seemingly virtual economic activities remain materially dependent on electricity-intensive technological systems [10]. The EC → BTC relationship may thus represent a development-sequencing effect in which expansion of energy infrastructure enables the expansion of digital financial activity.

This interpretation is especially relevant for Bangladesh and Indonesia, where disparities in energy access and infrastructure can constrain the development of digital ecosystems. The relationship between energy capacity and digital activity suggests that cryptocurrency growth in such contexts may follow infrastructure expansion rather than generate it. More generally, energy consumption is shaped by the technological and physical efficiency of national infrastructure. Research on energy performance in the built environment has demonstrated how infrastructural characteristics can significantly influence the amount of energy required to sustain economic and social activities [15]. Although that evidence concerns building performance rather than cryptocurrency markets, it supports the broader conclusion that energy-demand relationships are mediated by technological and infrastructural conditions. In countries where digital infrastructure remains constrained, electricity availability may therefore determine the feasible scale of cryptocurrency participation.

The absence of significant Bitcoin causality in Pakistan and Egypt provides further evidence of the importance of institutional barriers. A non-significant causal relationship does not necessarily imply that cryptocurrencies are absent from these economies; rather, it suggests that cryptocurrency activity is insufficiently integrated with the formal energy system to generate a detectable macroeconomic relationship. Restrictive policies, financial controls, regulatory uncertainty, and weak formal market integration may interrupt the transmission mechanisms that connect cryptocurrency activity with energy demand. This result accords with the view that institutional structures determine the incentives and opportunities available to market participants [16]. It also supports the argument that cryptocurrency adoption in emerging and Islamic markets is conditioned by regulatory legitimacy, financial structures, social acceptance, and institutional compatibility [2].

One of the most significant findings of the study concerns the relationship between non-energy-intensive cryptocurrencies and energy consumption. Although these cryptocurrencies are technologically less dependent on energy-intensive consensus mechanisms, significant causality from NON_ENCRYPTO to EC was identified in Iran, Pakistan, Bangladesh, and Egypt. This finding challenges the assumption that lower direct computational requirements necessarily translate into negligible system-level energy effects. The result can be interpreted through an indirect digital-infrastructure channel. Greater cryptocurrency activity stimulates demand for exchanges, servers, data storage, internet infrastructure, digital wallets, telecommunications services, and associated financial technologies. The increasing energy footprint of digital infrastructures documented in other technological domains reinforces the plausibility of this mechanism [10]. Thus, the energy consequences of cryptocurrency adoption may extend beyond the electricity consumed in consensus validation.

The finding can also be explained by the rebound effect. Improvements in technological energy efficiency do not always reduce aggregate energy use because lower energy requirements per unit of activity can lower effective costs and encourage greater utilization. The energy-efficiency literature has long documented this phenomenon, showing that part of the expected reduction in energy demand may be offset by increased consumption or activity following efficiency gains [11]. Applied to cryptocurrencies, lower-energy technologies may encourage broader participation, greater transaction volumes, and expansion of the cryptocurrency ecosystem, thereby generating indirect energy demand. Accordingly, the transition from energy-intensive to lower-energy cryptocurrencies should not automatically be equated with a proportional reduction in total system-level energy consumption.

A life-cycle perspective further supports this interpretation. Contemporary environmental analysis increasingly emphasizes that the environmental performance of a technology should incorporate upstream and downstream inputs rather than focusing exclusively on its most visible operational stage. Life-cycle energy research demonstrates that production pathways and associated infrastructure can create substantial indirect energy and environmental impacts [12]. In cryptocurrency ecosystems, this means that assessment should include computing devices, servers, data centers, telecommunications networks, exchanges, storage infrastructure, and complementary digital services. The findings of this study therefore suggest that a cryptocurrency categorized as "non-energy-intensive" on the basis of its consensus mechanism may nevertheless contribute to aggregate electricity demand through the expansion of the wider digital ecosystem.

The results for Türkiye and Malaysia provide an important counterpoint because the direction of causality in the second system ran from energy consumption to non-energy-intensive cryptocurrency activity. Both countries displayed comparatively strong associations of cryptocurrency activity with internet access and financial development. This pattern supports the argument that lower-energy cryptocurrencies become more strongly embedded as financial assets where digital and financial institutions are relatively mature. The finding aligns with research showing that cryptocurrency adoption depends substantially on technological acceptance and digital-system participation [20], while financial innovation more generally depends on market structure, infrastructure, and institutional development [1]. It is also consistent with previous evidence that cryptocurrencies increasingly behave as financial-market assets whose dynamics are shaped by broader financial conditions [4]. In these contexts, energy infrastructure may therefore facilitate digital-financial expansion without cryptocurrency activity necessarily becoming a major independent driver of national energy demand.

The significant positive coefficients for fossil-fuel dependence across the energy equations underscore a broader sustainability concern. The effect of cryptocurrency expansion depends not only on how much electricity is consumed but also on how that electricity is produced. D8 economies with high fossil-fuel shares face greater environmental costs from additional digital electricity demand than economies with cleaner generation portfolios. Previous research has emphasized the relationship between renewable-energy deployment and reductions in energy-security vulnerabilities [13]. Likewise, evidence from oil-rich developing countries indicates that investment in renewable infrastructure, human capital, and environmental sustainability is important for increasing renewable-energy consumption [14]. These studies support the implication that policies targeting cryptocurrency-related energy use should be integrated with broader strategies for energy transition and renewable infrastructure rather than being treated solely as financial or technological regulation.

Finally, the presence of cointegration in both cryptocurrency systems indicates that the observed relationships extend beyond short-run market fluctuations. Cryptocurrency markets and energy consumption appear to share long-run equilibrium dynamics despite substantial cross-country heterogeneity. This result complements research identifying significant linkages and spillovers between cryptocurrency and energy markets [17, 18]. Importantly, the stronger statistical evidence for the Bitcoin-based system is consistent with the structurally energy-intensive nature of Proof-of-Work mining documented in previous research [5-7]. Overall, the findings support a context-specific framework in which energy prices, fossil-fuel dependence, financial development, internet access, regulatory institutions, and technological structures jointly determine whether cryptocurrencies drive energy consumption, whether energy capacity drives cryptocurrency activity, or whether the two markets remain comparatively disconnected.

This study has several limitations that should be considered when interpreting its findings. First, the panel covers eight D8 countries over the 2015–2024 period, which provides an informative comparative setting but remains relatively limited in both cross-sectional and temporal dimensions. Second, national-level annual data may conceal substantial within-country heterogeneity, particularly because cryptocurrency mining, electricity subsidies, internet access, and digital financial activity can vary markedly across regions. Third, cryptocurrency activity is inherently difficult to measure because part of the market operates through decentralized platforms, informal transactions, peer-to-peer exchanges, virtual private networks, and unregistered mining facilities; therefore, market-price and capitalization indicators cannot capture all dimensions of country-specific cryptocurrency activity. Fourth, the constructed non-energy-intensive cryptocurrency index aggregates several assets with different technological architectures and market functions. Fifth, although the models included major economic, energy, digital, and institutional variables, other potentially relevant factors—such as electricity prices, mining hash rates, regulatory enforcement intensity, geopolitical shocks, exchange-rate volatility, and detailed renewable-energy composition—could not be fully incorporated because of limitations in consistent cross-country annual data. Finally, the comparative institutional analysis provides contextual interpretation of statistical findings but does not establish causal mechanisms independently of the econometric analysis.

Future studies should extend the analysis to larger samples of emerging, middle-income, and energy-exporting economies in order to determine whether the three identified patterns—cryptocurrency-driven, energy-driven, and disconnected systems—are generalizable beyond the D8 bloc. Research using monthly or quarterly data could capture short-run adjustments, regulatory shocks, cryptocurrency-market crashes, electricity shortages, and changes in mining incentives more precisely than annual observations. Future analyses could also replace aggregate cryptocurrency indicators with technologically differentiated measures based on Proof-of-Work, Proof-of-Stake, and other consensus mechanisms. Incorporating mining hash rates, country-level trading volumes, peer-to-peer transaction activity, electricity tariffs, renewable-energy shares, carbon intensity, data-center capacity, and cryptocurrency regulatory indices would improve identification of specific transmission channels. Nonlinear panel methods, threshold models, regime-switching approaches, quantile causality, time-varying parameter models, and spatial econometric techniques may also reveal whether the cryptocurrency–energy relationship changes under different levels of energy prices, financial development, or institutional quality. Micro-level research on miners, cryptocurrency users, exchanges, and digital-service providers would be particularly useful for examining the indirect energy-consumption channels identified in this study. Finally, future research should undertake comprehensive life-cycle assessments of lower-energy cryptocurrencies to determine whether reductions in direct validation energy are offset by ecosystem expansion, infrastructure demand, or rebound effects.

Policymakers should avoid adopting a uniform cryptocurrency–energy policy across countries with substantially different energy, financial, and institutional structures. In cryptocurrency-driven economies, regulation should focus on electricity pricing, mining licensing, energy-use disclosure, grid management, and incentives to shift computational activity toward low-carbon electricity. In energy-driven economies, priority should be given to improving electricity reliability, digital infrastructure, and the resilience of financial technology systems so that cryptocurrency expansion does not compete with essential energy needs. Countries in which cryptocurrency and energy markets are currently disconnected should develop transparent and predictable regulatory frameworks before market expansion produces large informal or unmonitored energy burdens. Governments should also distinguish between energy-intensive and lower-energy cryptocurrencies but should not assume that lower direct computational intensity automatically implies negligible environmental impact. Energy and financial regulators should jointly assess the electricity requirements of exchanges, data centers, servers, digital wallets, telecommunications networks, and other components of the cryptocurrency ecosystem. Renewable-energy development should be incorporated into cryptocurrency policy, particularly in fossil-fuel-dependent economies, while electricity subsidies should be designed to prevent unintended transfers toward privately profitable high-consumption activities. Finally, regional coordination among D8 countries should be strengthened through information sharing, common reporting standards, monitoring of cross-border cryptocurrency flows, and coordinated assessment of energy and financial risks.

Authors' Contributions

Authors equally contributed to this article.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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