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Quantifying Bidirectional Connectedness: A Quantile Analysis of Electricity Price Fluctuations and Industrial Production Dynamics in Colombia

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Abstract

This study explores the intricate relationship between electricity prices and industrial production, with a specific focus on scenarios within the mid-range and tail distribution. Recognizing the bidirectional impact between these variables, the analysis utilizes Colombian data, where 70% of electricity is hydroelectric and the rest is thermopower generated from fossil fuels. Climate-induced fluctuations affecting hydroelectric generation can influence electricity prices, subsequently impacting industrial production. The findings reveal that increased electricity prices adversely affect industrial production due to heightened production costs, while increased industrial production contributes to lower electricity prices, indicating a bidirectional impact. The study's implications suggest strategic planning opportunities, aligning production with electricity price fluctuations, and policy formulation to stimulate production for positive impacts on industrial production and overall economic growth.

Keywords: Electricity prices; industrial production; energy transition dynamics.

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Midiendo la conectividad bidireccional: un análisis cuantílico de las fluctuaciones del precio de la electricidad y la dinámica de la producción industrial en Colombia

Resumen

Este estudio analiza la relación entre los precios de la electricidad y la producción industrial, centrándose en los escenarios de precios promedios y extremos. Utilizando datos colombianos, donde el 70% de la electricidad proviene de fuentes hidroeléctricas y el resto de las plantas termoeléctricas alimentadas por combustibles fósiles, se revela un vínculo bidireccional entre estas variables. Las fluctuaciones climáticas que afectan la generación hidroeléctrica inciden en los precios de la electricidad y, a su vez, en la producción industrial. Se observa que el alza en los precios de la electricidad impacta negativamente la producción industrial debido a mayores costos, mientras que un incremento en la producción industrial puede reducir los precios de la electricidad, indicando una influencia mutua. Este estudio sugiere oportunidades estratégicas al alinear la producción con las fluctuaciones de los precios de la electricidad y formular políticas para estimular la producción e impulsar el crecimiento económico.

Palabras clave: precios de la electricidad; producción industrial; dinámica de la transición energética.

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1. Introduction

Determining optimal production levels is central to firm decision-making and is intrinsically linked to input costs, particularly in electricity-intensive industrial sectors. Electricity constitutes a strategic production input and accounts for a substantial share of global industrial energy consumption (Irfan *et al*., 2020). Variations in electricity prices therefore affect marginal production costs, operating margins, and competitiveness. A large empirical literature documents that higher electricity prices reduce industrial productivity and output through cost pass-through mechanisms (Abeberese, 2017; Allcott *et al.* 2016; Jo *et al.,* 2019), reinforcing the central role of productivity in economic growth and national performance (Durán Acosta & Zolano Sánchez, 2019; Alemán *et al.,* 2021).

More broadly, the electricity-industry nexus operates through multiple transmission channels. First, the cost channel implies that increases in electricity prices raise marginal production costs and compress industrial output. Second, a demand-feedback channel emerges as expansions in industrial activity increase electricity demand and influence price formation (Hoseinzadeh & Heyns, 2021; Tang *et al.,* 2016; Tiba & Omri, 2017). Third, a market-structure channel arises from the institutional design of electricity markets, where price shocks are often absorbed through higher production costs due to demand inelasticity

(Restrepo-Trujillo *et al.*, 2022) and competitive market dynamics (Chevez, 2018; Tsao *et al.,* 2021), potentially constraining growth under supply stress (Yu *et al.*, 2019). Finally, in hydro-dependent economies, a climate vulnerability channel magnifies these effects, as hydrological shocks alter electricity supply conditions and intensify price volatility (Arango-Aramburo *et al*., 2019; Hamududu & Killingtveit, 2012; Poveda *et al.,* 2011; Turner *et al.*, 2017).

We focus on Colombia, a hydro-dominant economy whose electricity market operates under a centralized wholesale scheme with a hydrothermal generation mix and a uniform marginal pricing (UMP) mechanism with merit-order dispatch. Approximately 65-70% of electricity generation is hydroelectric (Arango-Aramburo *et al*., 2019). The day-ahead spot market clears at the system marginal price (SMP), meaning that all dispatched generators receive the marginal unit price. Under this pay-as-cleared design, reductions in hydro availability—particularly during ENSO episodes—force the entry of higher-cost thermal plants, raising the marginal price for the entire system (Poveda *et al*., 2011). This institutional structure amplifies the pass-through of climate-induced supply shocks to electricity prices and, consequently, to industrial production.

The Colombian electricity market operates under a regulatory framework established by the Energy and Gas Regulation Commission (CREG), which defines market rules, tariff structures, and the components of the final electricity price. It is important to distinguish between the wholesale spot price analyzed in this study—determined through marginal cost pricing in the day-ahead market administered by XM—and the final regulated tariff paid by end users, which includes additional components such as transmission, distribution, commercialization, and regulatory charges. Theis analysis focuses exclusively on wholesale spot price dynamics.

This study advances the literature in three key dimensions. First, while existing research largely examines average effects, we explicitly model distributional heterogeneity and demonstrate that the electricity-industry linkage is nonlinear and significantly stronger in extreme states. Second, we integrate climate vulnerability into the analysis of energy-industry interactions, showing that hydro-dependence structurally amplifies transmission mechanisms during ENSO-related stress periods. Third, by combining a VAR framework (Sims, 1980) with spillover measures (Diebold & Yilmaz, 2012) extended to a quantile setting (Chatziantoniou *et al.,* 2021), we provide a tail-sensitive assessment of bidirectional interconnectedness within a parsimonious two-variable system.

Our findings indicate that electricity price increases exert a statistically significant negative effect on industrial production, validating the cost-channel hypothesis, while industrial production also influences electricity price dynamics, particularly under climate-related stress regimes. These results demonstrate that the electricity-industry nexus in hydro-dependent economies is multidimensional, bidirectional, nonlinear, and strongly state-dependent.

From a policy perspective, reducing hydrological vulnerability through diversification of the generation matrix is essential to stabilize electricity prices and protect industrial competitiveness. Although hydropower is renewable, excessive reliance on a single renewable source increases exposure to climate shocks; expanding complementary renewable technologies can attenuate volatility, enhance system resilience, and function as a macroeconomic stabilization mechanism. Energy transition policies therefore represent not only environmental commitments but also structural instruments for sustaining industrial growth. This paper is organized into distinct sections, encompassing the introduction, reference framework, methodology, results, and conclusion.

2. Reference Framework

Productivity constitutes a fundamental pillar of economic development, as it enables efficient resource allocation, cost minimization, and enhanced competitiveness (Alemán *et al.*, 2021). At the macroeconomic level, improvements in productivity translate into sustained economic growth, whereas inefficiencies constrain national performance (Durán Acosta & Zolano Sánchez, 2019). Within this framework, electricity emerges as a strategic production input, particularly in the industrial sector, which accounts for nearly half of global electricity consumption (Irfan *et al.*, 2020). Given its significant role in the production function, variations in electricity prices and availability influence industrial performance through multiple interconnected transmission channels.

The most direct mechanism operates through the cost channel. Electricity is an essential intermediate input; therefore, increases in electricity prices raise marginal production costs, compress profit margins, and potentially reduce output. Empirical evidence consistently supports this mechanism. Dechezleprêtre and Sato (2017) document that higher electricity prices significantly increase firms' operating costs and directly affect productivity. Jo *et al.* (2019) show that energy price fluctuations alter production decisions via cost pass-through effects, while Huynh *et al.* (2023) emphasize that stable electricity supply is crucial for maintaining productivity levels. Micro-level studies—including Abeberese (2017), Jamil and Ahmad (2010), Allcott *et al.* (2016), Kassem (2024), and Dhoska *et al*. (2024)—confirm that higher electricity prices negatively affect industrial performance, particularly in energy-intensive sectors.

A second mechanism operates through an efficiency and adjustment channel. Firms respond strategically to electricity price signals by optimizing production systems, adopting energy-efficient technologies, or reallocating resources. Qadan and Nama (2018) argue that rising electricity prices can induce technological upgrading and operational integration, while Magazzino (2015) links electricity spot prices to industrial decision-making and productivity growth. Similarly, Bjerregaard and Møller (2022) highlight that electricity prices act as incentives that shape firm-level strategic adjustments. Although such responses may mitigate long-run cost pressures, the short-run effect of price increases remains predominantly contractionary.

A third channel relates to market structure and supply constraints. Electricity has evolved into a tradable economic good embedded within competitive market dynamics (Chevez, 2018; Tsao *et al.,* 2021). However, electricity demand is relatively inelastic in the short term (Restrepo-Trujillo *et al.*, 2022), limiting firms' ability to substitute away from energy inputs. Consequently, price shocks are often absorbed through higher production costs rather than reduced consumption. Yu *et al*. (2019) further argue that energy supply constraints relative to demand can suppress economic growth, reinforcing the macroeconomic importance of reliable generation capacity.

Beyond price effects, the literature also emphasizes the causal and bidirectional relationship between electricity consumption, generation, and production growth. Acheampong *et al*. (2021) show that economic expansion drives sustained increases in electricity demand, highlighting the need for strategic investment in generation capacity. Empirical studies such as Tang *et al.* (2016), Tiba and Omri (2017), and Hoseinzadeh and Heyns (2021) identify bidirectional or Granger-causal relationships between electricity consumption and industrial production. Similarly, Azam *et al*. (2021), Cardoso Marques *et al.* (2016), Abbasi *et al.* (2021), Burke *et al.* (2019), and Shahbaz *et al*. (2017) document that electricity generation and consumption significantly contribute to both short-run and long-run production growth. Sun and Anwar (2015) find stable long-run bidirectional relationships in manufacturing sectors, while Xie and Huang (2025) underline the role of electricity prices and subsidies in shaping industrial resource allocation and technological progress.

In hydro-dependent economies, these mechanisms are further conditioned by climate vulnerability. Hydropower output depends directly on precipitation and runoff, implying that climate anomalies translate into supply-side constraints that increase electricity prices and amplify cost pressures on the industrial sector. Globally, hydropower generation is sensitive to climate-driven changes in water availability (Hamududu & Killingtveit, 2012), creating systemic risk in renewable-dominant systems. This vulnerability is particularly pronounced in Colombia, where climate change scenarios imply hydropower losses that must be offset by diversification and technological adaptation (Arango-Aramburo *et al*., 2019). ENSO-related variability significantly affects hydro-climatic conditions in the Colombian Andes, with El Niño episodes reducing rainfall and river discharges, thereby constraining hydroelectric generation (Poveda *et al.,* 2011). Evidence from high-resolution hydropower modeling further shows that climate change can materially alter generation outcomes and increase electricity system vulnerability (Turner *et al.,* 2017).

Under such climate-induced stress regimes, electricity prices become stronger transmitters of shocks to industrial production via the cost channel. Hydrological constraints increase marginal generation costs, heighten price volatility, and intensify cross-sector spillovers. Consequently, the electricity-industry nexus becomes nonlinear and state-dependent, with transmission mechanisms strengthening under extreme conditions.

Taken together, the literature supports a multidimensional and bidirectional relationship between electricity and industrial production, operating through (i) cost pass-through effects, (ii) efficiency adjustments, (iii) supply-demand and market structure mechanisms, and (iv) climate vulnerability in hydro-dependent systems. Electricity therefore functions not only as a production input but also as a macroeconomic stabilizer whose reliability and price stability are central to sustained industrial growth. Our empirical analysis builds on this framework by demonstrating that these transmission mechanisms are nonlinear and significantly amplified in the tails of the distribution, particularly under climate-related stress conditions.

Based on the above, the following hypotheses are proposed:

H1: The prices of electricity negatively impact the country's industrial production.

H2: There is a greater connection between electricity prices and industrial production in extreme scenarios, particularly during climate-related stress periods in hydro-dependent systems.

3. Methodology

To examine the dynamic interaction between electricity prices and industrial production, we adopt a Vector Autoregressive (VAR) framework originally proposed by Sims (1980). The VAR approach treats all variables as endogenous, allowing for bidirectional dynamic feedback effects, when

$$x_t = (IP_t, EP_t)' \tag{1}$$

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x_t represents the vector of endogenous variables with dimensions $kx1$. IP_t represents industrial production and EP_t denotes electricity prices. The standard VAR(p) model is specified as:

$$x_t = \boldsymbol{\mu} + \sum_{i=1}^{p} \Phi_i x_{t-i} + \varepsilon_t \tag{2}$$

μ is a $kx1$ vector of intercepts, Φ_i are kxk coefficient matrices, p denotes the optimal lag length. ε_t represents the error $kx1$. This reduced-form representation captures the joint dynamics between industrial production and electricity prices without imposing a priori causal restrictions.

To quantify the transmission of shocks between variables, we employ the Generalized Forecast Error Variance Decomposition (GFEVD) proposed by Pesaran and Shin (1998) and operationalized in the connectedness framework of Diebold & Yilmaz (2012). The moving average representation of the VAR is:

$$x_t = \sum_{h=0}^{\infty} \Phi_i \varepsilon_{t-h} \tag{3}$$

Φ_i is de impulse response coefficients matrices. The generalized variance decomposition measuring the contribution of shocks in variable j to the forecast error variance of variable i at horizon H is given by:

$$\theta_{ij}^{g}(H) = \frac{\sum \sum_{h=0}^{H-1} \left(e_i' \Phi_h \Sigma e_j\right)^2}{\sum_{h=0}^{H-1} (e_i' \Phi_h \Sigma \Phi_h' e_i)} \tag{4}$$

$\boldsymbol{e}_i$ is a selection vector with unity in the $i-th$ position and zeros elsewhere $\sum$ is the covariance matrix of innovations. Due to the generalized approach does not impose orthogonality, row sums do not necessarily equal unity. Therefore, normalization is required.

$$\tilde{\theta}_{ij}^{g}(H) = \theta_{ij}^{g}(H) \left[\sum_{j=1}^{k} \theta_{ij}^{g}(H) \right]^{-1} \tag{5}$$

Where:

$$\sum_{j=1}^{k} \tilde{\theta}_{ij}^{g}(H) = 1 \tag{6}$$

Following Diebold and Yilmaz (2012), we compute directional spillovers. The total directional connectedness transmitted from variable j to all other variables is:

$$s_{j\to i}^{g}(H) = \sum_{i=1, i\neq j}^{k} \tilde{\theta}_{ij}^{g}(H) \tag{7}$$

Conversely, the total directional connectedness received by variable iii from all other variables is:

$$s_{j\to i}^{g}(H) = \sum_{j=1, i\neq j}^{k} \tilde{\theta}_{ij}^{g}(H) \tag{8}$$

The Total Connectedness Index (TCI), which measures the overall degree of spillover in the system, is defined as:

$$TCI(H) = \frac{\sum_{j=1, i\neq j}^{k} \tilde{\theta}_{ij}^{g}(H)}{k} \tag{9}$$

Because climate-related energy shocks (e.g., ENSO events) generate asymmetric and tail-dependent dynamics, mean-based VAR models may not capture extreme-state interdependencies. To address this limitation, we extend the framework using the Quantile Vector Autoregression (QVAR) approach developed by Chatziantoniou *et al.* (2021). For each quantile $\tau \in (0,1)$ the QVAR(p) is specified as:

$$x_t(\tau) = \boldsymbol{\mu}(\tau) + \sum_{i=1}^{p} \Phi_i(\tau) x_{t-i} + \varepsilon_t(\tau) \tag{10}$$

where parameters are estimated conditional on the $\tau - th$ quantile of the distribution.

$$\tilde{\theta}_{ij}^{g}(H, \boldsymbol{\tau}) \tag{11}$$

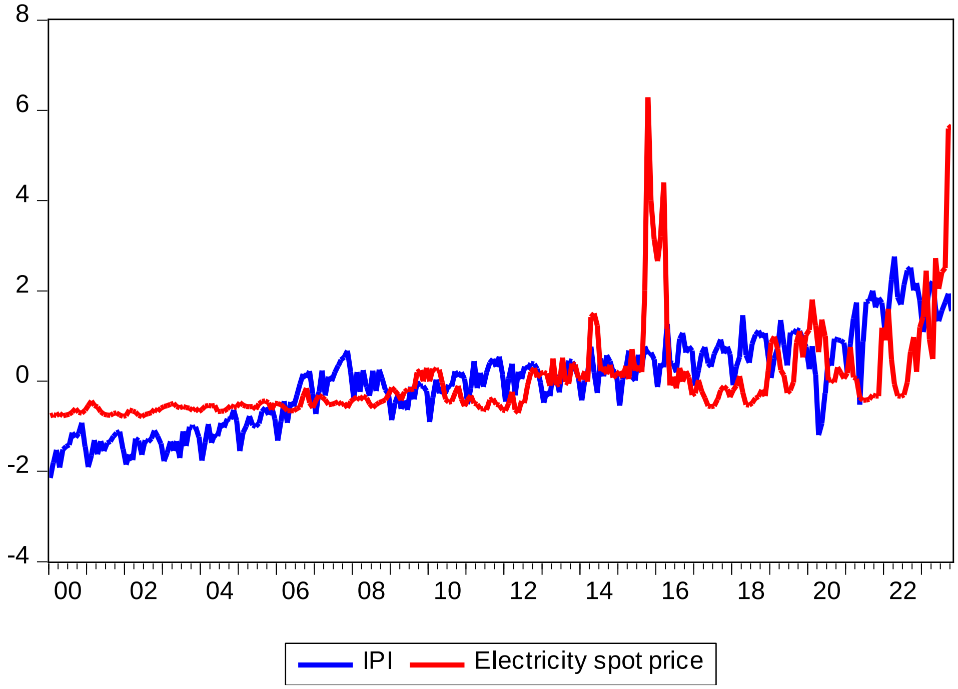
thereby enabling the analysis of spillover dynamics across the entire conditional distribution, including lower-tail (stress) and upper-tail (expansion) regime.

3.1. Data

The impact of electricity price shocks on industrial production in Colombia was investigated using monthly data spanning January 2000 to October 2023 (286 observations). The analysis employed the following data sources: (1) Industrial Production Index (IPI) from the Central Bank of Colombia (Banco de la República de Colombia), and (2) Colombia's spot electricity price from the XM Information System.

Figure 1 depicts the normalized Industrial Production Index (IPI) and electricity spot price to facilitate an analysis of their dynamic behavior. The IPI exhibits a general upward trend with some minor fluctuations. Its peak is consistent with the strong economic growth in 2022 following the initial shock of the covid-19 pandemic. Conversely, a significant downward trend is observed in 2020, reflecting the pandemic's immediate impact. In contrast, the electricity spot price displays substantial variability, marked by major spikes in 2014, 2016, and 2023. Notably, the period from 2017 to 2022 reveals an almost inverse relationship between the two variables, with rising IPI coinciding with falling electricity prices and vice versa.

Figure 1. Industrial Production Index (IPI) and Electricity Spot Price for Colombia with Normalized Data.



Source. Own elaboration.

Table 1 reports the descriptive statistics for the two variables used in the empirical analysis: RLP and RIPI. RLP denotes the first difference of the logarithm of electricity spot prices, while RIPI represents the first difference of the logarithm of industrial production. Both series were transformed into logarithms and subsequently differenced to ensure stationarity. Unit root tests (available upon request) confirm that the variables are integrated of order one, I(1), and become stationary after first differencing. This transformation is a necessary condition for estimating a stable and well-specified VAR model, as it avoids spurious regression problems and ensures that the system satisfies standard time-series assumptions.

The use of log-differences provides a growth-rate interpretation and allows for a clearer assessment of shocks transmission over time. Regarding central tendency, RLP exhibits higher mean and median values (mean: 0.005039; median: 0.001072), indicating that electricity prices display larger average monthly growth fluctuations compared to industrial production (RIPI). However, RLP also shows considerably greater dispersion, with a standard deviation of 0.121856 relative to 0.031562 for RIPI, suggesting that electricity prices are substantially more volatile than industrial production.

In terms of distributional properties, RLP shows slight positive skewness (0.367507), implying a longer right tail, whereas RIPI exhibits negative skewness (-0.535736), indicating a longer left tail. Both variables display excess kurtosis (RLP: 4.94; RIPI: 4.64), revealing heavier tails relative to the normal distribution. The Jarque-Bera statistics strongly reject normality for both series (p-values = 0.000), reinforcing the presence of fat tails and asymmetric behavior—features commonly observed in energy price data.

Examining the range, RLP shows a substantially wider spread between its minimum (-0.397703) and maximum (0.505997) values compared to RIPI (minimum: -0.15602; maximum: 0.102726). This broader range suggests the presence of extreme price adjustments in electricity markets, consistent with supply shocks and shock clustering. Similarly, the sum and sum of squared deviations are considerably higher for RLP (sum: 1.44; sum sq. dev.: 4.22) than for RIPI (sum: 0.31; sum sq. dev.: 0.28), further reflecting the greater magnitude and variability of electricity price fluctuations.

Although both series contain the same number of observations (285), their descriptive statistics highlight markedly different stochastic properties. Electricity prices exhibit higher shock, stronger deviations from normality, and more pronounced extreme movements relative to industrial production growth. Ensuring stationarity in first differences allows these dynamics to be appropriately modeled within the VAR framework, thereby enabling consistent estimation of the dynamic interrelationships analyzed in the subsequent sections.

Table 1. Statistics

	RLP	RIPI
Mean	0.005039	0.001072
Median	0.006979	0.003323
Maximum	0.505997	0.102726
Minimum	-0.397703	-0.15602
Std. Dev.	0.121856	0.031562
Skewness	0.367507	-0.535736
Kurtosis	4.94	4.64
Jarque-Bera	5.11	4.54
Probability	0.000000	0.000000
Sum	1.44	0.31
Sum Sq. Dev.	4.22	0.28
Observations	285	285

Source. Own elaboration.

4. Results

Figure 2 reports the impulse response function (IRF) to a two-standard-deviation shock in electricity prices (RLP) on industrial production (RIPI). Prior to estimation, standard diagnostic tests were performed to ensure correct model specification. The optimal lag length was selected to eliminate residual serial correlation up to 28 lags, as confirmed by LM tests. Under this specification, the null hypothesis of no residual autocorrelation could not be rejected, indicating that the VAR satisfies the stability and white-noise error assumptions required for consistent estimation and valid inference. The model was then estimated and used to compute the impulse response function.

In figure 2, the blue line represents the magnitude and direction of the response of industrial production to the electricity price shock. Positive values indicate that an increase in electricity prices exerts a positive effect on industrial production, whereas negative values imply a contractionary effect. The red lines correspond to the confidence intervals. Responses are considered statistically significant when these intervals do not include zero.

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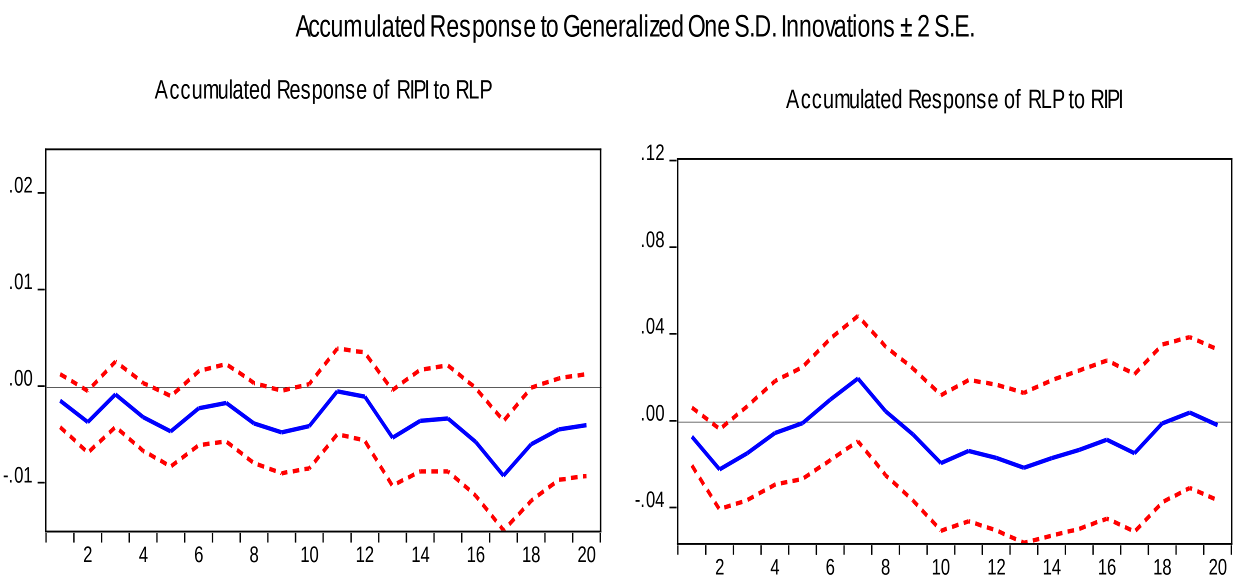
The results reveal a statistically significant decline in industrial production following a positive electricity price shock. This negative effect becomes evident around the fifth month and remains significant at several horizons (approximately periods 2, 5, 7, 13, and 17). Economically, this finding suggests that higher electricity prices increase production costs, thereby reducing industrial output.

Interestingly, the impulse response analysis also indicates evidence of bidirectional dynamics. A positive shock to industrial production generates a temporary reduction in electricity prices, particularly around the second month. One plausible explanation is that higher levels of industrial activity may increase electricity supply through self-generation or industrial-linked thermoelectric production, thereby exerting downward pressure on market prices. This reciprocal adjustment mechanism further supports the existence of interconnected energy-industry dynamics within the system.

Importantly, the bidirectional effect identified corresponds to short-run conditional dynamics within the VAR-Q framework and does not imply a structural inversion of the Colombian merit-order pricing mechanism. Rather, it reflects temporary demand-supply adjustments captured econometrically under specific market conditions.

Figure 2. IRF between Electricity Spot Price and Industrial Production



Note. The VAR model is estimate to 28 lags.

Source. Own elaboration.

Table 2 analyzes the spillover between markets by measuring the impact of forecast errors in one market (i) on the shock of another (j). Each row shows the proportion of market shock from j that is attributable to other markets, while each column details the contribution of each market to the shock of the rest. Industrial production receives 11.25% of its shock from the electricity spot price, and the electricity spot price receives 13.86% of its shock from industrial production. This indicates a significant bidirectional transmission of shock between these two markets.

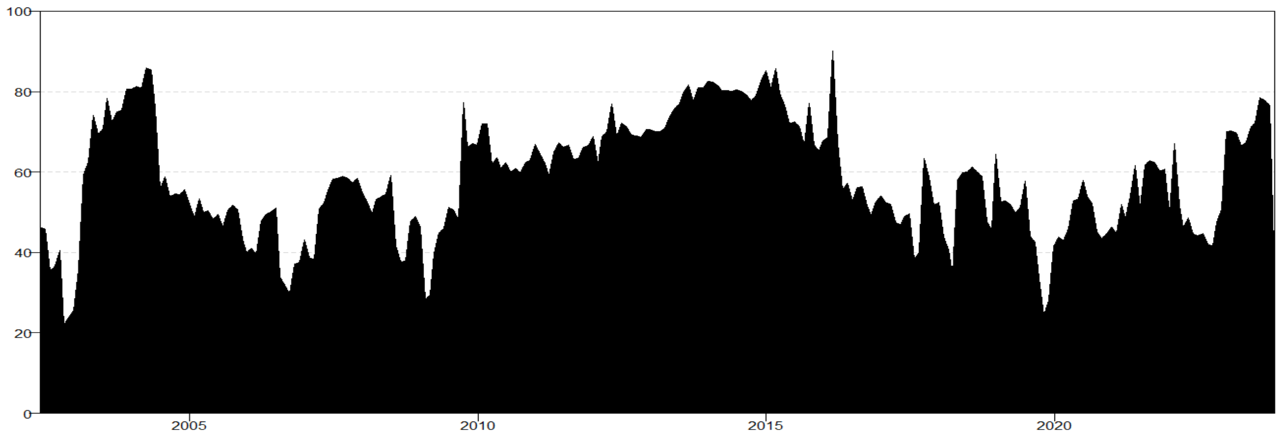
Table 2. Shock Spillover

	RIPI	RLP	FROM Other
RIPI	88.75	11.25	11.25
RLP	13.86	86.14	13.86
TO	13.86	11.25	25.1
Inc.Own	102.61	97.39	

Source. Own elaboration.

Figure 3 shows the temporal evolution of the interconnectedness dynamics among the variables, where higher levels indicate a significant increase in connectivity. We can observe that the level of connections is not static but rather fluctuates across the timeframe. Notably, two distinct periods of exponential growth in connectedness are evident, for example, 2002-2004. During this early period, the network of connections rapidly expands, suggesting a surge in interdependence between the variables. 2009-2016: This later period marks another phase of significant growth in connectedness, potentially indicating the emergence of new relationships or strengthening of existing ones. Additionally, the figure highlights a peak in connectedness in 2023, hinting at a renewed emphasis on interconnectedness in the most recent data. Overall, the figure underscores the dynamic nature of the relationships between these variables, with periods of both relative stability and rapid change.

Figure 3. Dynamic Connection of Variables



Note. Results based on VAR(1) model with a rolling window of 20 month and a 5-step-ahead forecast error variance decomposition.

Source. Own elaboration.

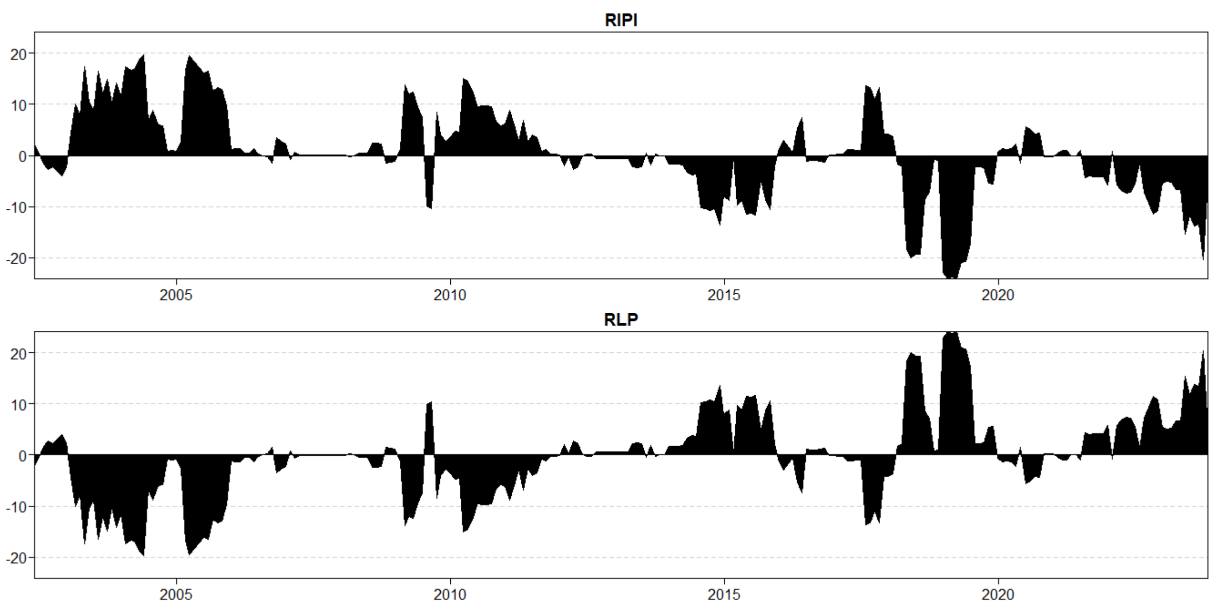
Figure 4 illustrates the time-varying net shock spillovers between industrial production (RIPI) and electricity prices (RLP). The figure reports net directional connectedness, where positive values indicate that the variable acts as a net transmitter of shocks, while negative values indicate that it behaves as a net receiver. The RIPI panel captures the net spillover position of industrial production, whereas the RLP panel reflects the corresponding dynamics for electricity prices.

The results reveal clear regime-dependent transmission patterns. During periods of relatively strong industrial performance—such as 2002-2007, 2009-2012, and 2017—industrial production predominantly acts as a net transmitter of shocks to electricity prices. This suggests that demand-side pressures associated with higher industrial activity contribute to electricity price dynamics, reinforcing a demand-driven transmission mechanism.

In contrast, during episodes characterized by weaker industrial performance—particularly 2009, 2012-2016, 2018-2019, and from 2021 onward—electricity prices emerge as net transmitters of shocks to industrial production. In these regimes, supply-side or cost-related disturbances in the electricity market propagate to the real sector, consistent with a cost-channel effect whereby higher energy prices increase production costs and dampen output.

Overall, the evidence underscores the dynamic and asymmetric nature of spillover transmission between the energy and industrial sectors. The direction and magnitude of these net spillovers vary across economic regimes, highlighting the importance of accounting for time-varying interdependence in energy-industry linkages. Such insights are relevant for policymakers and market participants concerned with energy market stability, industrial competitiveness, and systemic risk management.

Figure 4. Net Shock Spillovers



Source. Own elaboration.

Figure 5 shows the time-quantile evolution of total system connectedness derived from the Quantile VAR-based Diebold-Yilmaz framework. The horizontal axis (x-axis) represents time, while the vertical axis (y-axis) corresponds to the quantiles of the conditional distribution. The heatmap displays the Total Connectedness Index (TCI), where warmer tones indicate stronger shock transmission between electricity prices and industrial production across different points of the distribution and over time.

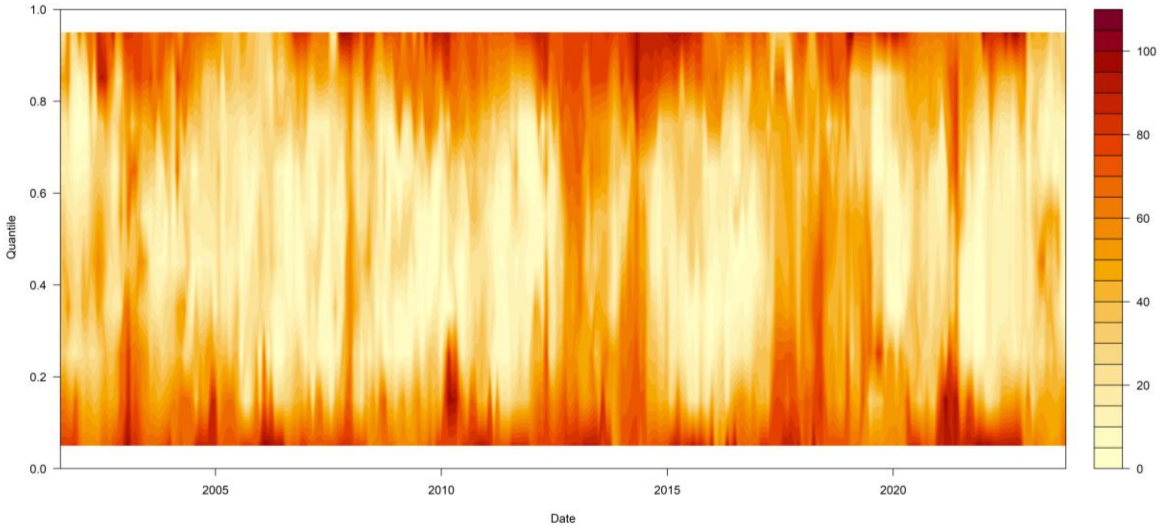
The results show a clear pattern across the distribution. Connectedness is strongest in the lower and upper quantiles, which represent extreme states of industrial production (either unusually low or unusually high growth). In these situations, shocks in electricity prices explain a larger portion of the variation in industrial production, and vice versa. This indicates that the interaction between the energy market and the industrial sector becomes more intense when the system moves away from normal conditions.

By contrast, during periods associated with the central part of the distribution—such as 2003, 2013-2014, 2017-2019, and 2023—connectedness increases more uniformly across quantiles. Several of these episodes coincide with periods of elevated electricity prices, including the strong El Niño event of 2015-2016 (with effects extending into 2017) and the confirmed El Niño episode of 2023. This suggests that high price regimes, regardless of whether they are driven by climatic shocks or other supply constraints, tend to strengthen the interdependence between electricity prices and industrial activity.

Importantly, the analysis does not reveal a markedly different spillover structure during conventional macroeconomic crises. This implies that the amplification of connectedness appears to be more closely related to energy market stress and price dynamics than to broad-based economic downturns.

Overall, the evidence confirms that interconnectedness is state-dependent: it intensifies under extreme production conditions and during periods of high electricity prices, reinforcing the nonlinear nature of the electricity-industry transmission mechanism.

Figure 5. Total System Connectivity across Time and Quantiles



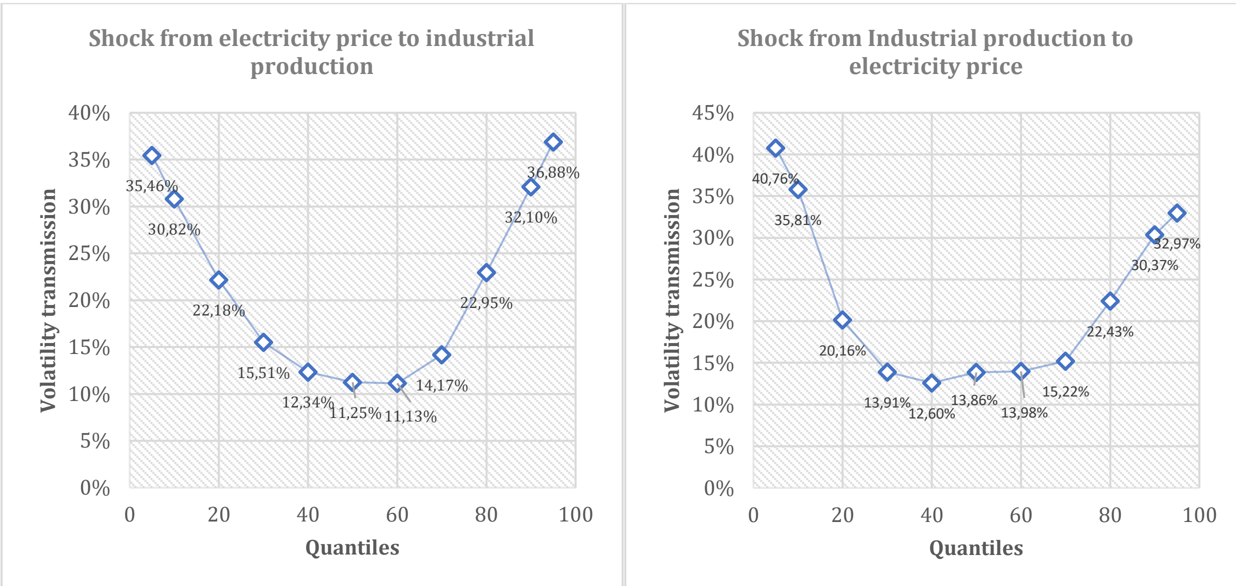
Source. Own elaboration

Figure 6 shows the magnitude of net shock transmission across the conditional distribution, spanning from the 5th to the 95th percentile. The results reveal a clear nonlinear pattern. Transmission levels remain relatively moderate within the central region of the distribution, but increase markedly as the system moves toward the lower and upper tails. This indicates that cross-variable spillovers intensify under extreme states of the system.

In the central quantiles, industrial production transmits approximately 13% of its shocks to electricity prices. However, this contribution rises substantially in the tails, reaching nearly 40% in the lower quantile and about 33% in the upper quantile. A similar pattern is observed in the opposite direction. Electricity prices transmit around 11% of their shocks to industrial production in the central region, but this share increases to approximately 35% in the lower tail and 37% in the upper tail.

These results confirm that shock transmission is strongly state-dependent. Under extreme conditions, whether associated with unusually low or high realizations, interdependence between electricity prices and industrial production becomes significantly stronger. This tail amplification underscores the nonlinear nature of the electricity-industry linkage and highlights the importance of accounting for distributional heterogeneity when evaluating spillover dynamics.

Figure 6. Shock across Quantiles

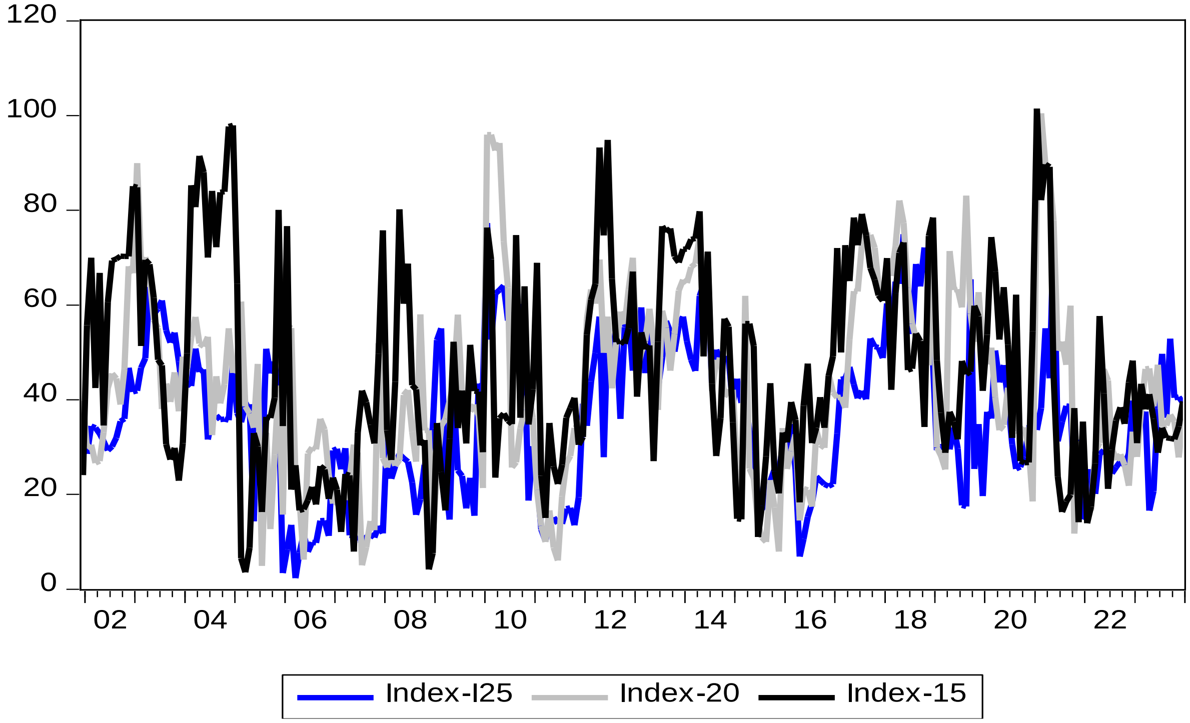


Source. Own elaboration.

4.1. Robustness Check

Figure 7 depicts the behavior of the connectedness index in the average model across window sizes of 15, 20, and 25. Notably, the index exhibits remarkable stability across these varying time horizons, suggesting a robustness of the underlying model. We observe fluctuations in the connectedness across different periods within each window size, indicating that the network dynamics are not entirely static.

Figure 7. Robustness Check



Source. Own elaboration.

Our findings are closely aligned with the existing literature on the relationship between electricity prices and industrial performance. Consistent with Irfan *et al*. (2020), we find that electricity spot prices exert a statistically significant and economically meaningful influence on industrial production. The negative response of industrial output to electricity price shocks confirms the relevance of the cost-channel mechanism: higher energy prices increase marginal production costs, compress operating margins, and reduce output. This evidence is consistent with Abeberese (2017), Jo *et al.* (2019), and Allcott *et al.* (2016), who document that increases in energy prices adversely affect productivity, investment, and industrial performance, particularly in energy-intensive sectors.

However, our results extend beyond the conventional unidirectional cost effect. We uncover robust evidence of bidirectional spillovers between electricity prices and industrial production, suggesting that the energy-industry nexus operates through mutually reinforcing feedback mechanisms. While electricity price increases dampen industrial activity via higher input costs, fluctuations in industrial production also influence electricity price dynamics through demand-side pressures and generation adjustments. This reciprocal interaction is consistent with Tang *et al.* (2016), who emphasize the interdependence between energy consumption and economic activity. In hydro-dependent systems, this feedback becomes more pronounced due to the structural integration between industrial demand and generation capacity, especially when thermoelectric plants compensate for hydroelectric variability.

A central contribution of this study lies in identifying the nonlinear and state-dependent nature of this relationship. Using a Quantile VAR framework, we show that spillover intensities vary significantly across the conditional distribution. Transmission effects are substantially stronger in the lower and upper tails than around the median, indicating that the interaction between electricity prices and industrial production intensifies under extreme conditions. This tail dependence suggests that the electricity-industry nexus is regime-dependent rather than constant over time.

The amplification observed in the tails is particularly consistent with the climate vulnerability channel documented in the literature. Hydropower generation is highly sensitive to climate variability, especially in systems with a dominant hydro share (Hamududu & Killingtveit, 2012). In the Colombian case, climate change scenarios imply hydropower losses that must be offset through diversification and adaptation of the generation matrix (Arango-Aramburo *et al*., 2019). Moreover, ENSO-related hydrological anomalies significantly reduce rainfall and river discharges in the Colombian Andes, directly constraining hydroelectric output (Poveda *et al.,* 2011). High-resolution modeling evidence further confirms that climate variability increases systemic vulnerability in hydro-based electricity systems (Turner *et al.,* 2017).

During ENSO-related hydrological stress, reductions in hydroelectric generation tighten electricity supply and increase reliance on higher-cost alternatives, thereby magnifying the cost channel and strengthening transmission from electricity prices to industrial production. Under these stress regimes, electricity price shocks explain a larger share of the variability in industrial output, reinforcing systemic interconnectedness and amplifying spillovers. Climate-induced supply constraints thus function as structural catalysts that intensify cross-sector transmission mechanisms.

Taken together, the empirical evidence provides strong support for both hypotheses. H1 is validated through the statistically significant and negative cost-channel effect of electricity prices on industrial production. H2 is confirmed by the presence of stronger spillovers in the tails of the distribution, particularly during climate-related stress periods, demonstrating that the electricity-industry linkage strengthens in extreme scenarios.

Overall, the results underscore the importance of incorporating climate risk, distributional heterogeneity, and state-dependent dynamics into models of energy-industry interactions. By moving beyond mean-based approaches, this study provides a more comprehensive understanding of how electricity price shocks propagate in hydro-dependent economies, especially under extreme hydrological and market conditions.

5. Conclusion and Policy Implications

This study examined the dynamic relationship between electricity prices and industrial production in Colombia, an economy characterized by a predominantly hydroelectric power matrix complemented by thermoelectric generation. This structural configuration makes the energy system highly dependent on hydrological conditions and therefore particularly vulnerable to climate variability, especially during ENSO-related drought episodes. Under such circumstances, reductions in reservoir levels constrain hydroelectric output and increase reliance on thermoelectric generation, intensifying price pressures and exposing the industrial sector to cost shocks.

The empirical evidence confirms the existence of a bidirectional and nonlinear relationship between electricity prices and industrial production. On the one hand, increases in electricity prices exert a negative effect on industrial output through the cost channel. On the other hand, expansions in industrial production influence electricity price dynamics, reflecting structural interdependence between the real sector and the energy market. Importantly, these effects are significantly amplified in extreme states of the distribution, where the transmission mechanism becomes substantially stronger. In tail scenarios, excessively high electricity prices reduce industrial production, while extreme price declines can still affect output by up to 35%, highlighting the system's sensitivity to price instability.

These findings carry important policy implications. Stabilizing the energy system requires reducing its exposure to climate-induced supply constraints. One effective mechanism is the implementation of targeted incentives to diversify the electricity generation matrix. Expanding generation capacity—particularly through complementary renewable sources such as solar and wind—can reduce dependence on hydrological conditions, mitigate price volatility, and weaken the amplification of cost shocks. Although hydroelectricity itself is a renewable source, a hydro-dominant system remains highly climate-sensitive. Therefore, diversification within the broader renewable spectrum is essential to enhance resilience.

Crucially, such incentives should be aligned with a coherent energy transition strategy. Policies that promote renewable diversification not only contribute to decarbonization objectives but also strengthen macroeconomic stability and industrial competitiveness by stabilizing electricity prices. In hydro-dependent economies, energy transition is not merely an environmental agenda, it is a structural tool to reduce systemic vulnerability to climate variability and to protect industrial productivity from extreme price movements.

From a strategic standpoint, industrial firms must also incorporate energy price risk into production planning and investment decisions. Greater coordination between energy policy and industrial policy can foster a more resilient economic structure, ensuring that electricity market stability supports sustained industrial growth.

In sum, this study demonstrates that in hydro-dependent economies, the electricity-industry nexus is dynamic, nonlinear, and climate-sensitive. Diversifying the generation matrix through transition-consistent renewable expansion emerges as a key policy lever to stabilize the energy system, reduce vulnerability to climate shocks, and enhance long-term industrial competitiveness.

Competing Interests. *The authors declare that they have no competing interests*

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