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ELECTRICITY PRICE FORMATION IN COLOMBIA: DOMESTIC AND EXTERNAL DETERMINANTS

FORMAÇÃO DE PREÇOS DE ELETRICIDADE NA COLÔMBIA: DETERMINANTES DOMÉSTICOS E EXTERNOS

FORMACIÓN DEL PRECIO DE LA ELECTRICIDAD EN COLOMBIA: DETERMINANTES DOMÉSTICOS Y EXTERNOS

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ABSTRACT

Electricity price stability represents a central challenge for hydropower-dependent economies navigating low-carbon energy transitions under climate variability. This article examines the determinants of electricity prices in Colombia (2005–2023) using a Vector Autoregression (VAR) model incorporating international natural gas prices (Henry Hub), domestic gas consumption, reservoir levels, and average electricity prices. Impulse Response Functions (IRFs) and Forecast Error Variance Decomposition (FEVD) are applied to assess interactions between domestic and external factors, complemented by Granger causality tests. Results indicate that price formation is predominantly driven by domestic factors; external shocks produce positive but transitory effects, dissipating within approximately ten months. Hydrological conditions and domestic gas consumption exert moderate indirect influences. The Colombian electricity market shows short-term resilience to external shocks but remains vulnerable to climate-driven hydrological variability, underscoring the need to diversify the energy mix and strengthen regional integration.

Keywords: Colombian Electricity Market. Electricity Prices. VAR Model. Energy Security. Price Dynamics.

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RESUMO

A estabilidade dos preços de eletricidade é um desafio central para economias dependentes da hidroenergia em transições energéticas de baixo carbono. Este artigo analisa os determinantes dos preços de eletricidade na Colômbia (2005–2023) via modelo VAR que incorpora preços internacionais do gás natural (Henry Hub), consumo doméstico de gás, níveis dos reservatórios e preços médios de eletricidade. Funções de Impulso-Resposta (FIR), Decomposição da Variância do Erro de Previsão (FEVD) e causalidade de Granger avaliam as interações entre fatores domésticos e externos. Os resultados mostram predominância doméstica; choques externos geram efeitos positivos, porém transitórios, dissipando-se em cerca de dez meses. Condições hidrológicas e consumo de gás exercem influências indiretas moderadas. O mercado colombiano apresenta resiliência de curto prazo, mas permanece vulnerável à variabilidade hidrológica, ressaltando a necessidade de diversificar a matriz energética e fortalecer a integração regional.

Palavras-chave: Mercado Elétrico Colombiano. Preços de Eletricidade. Modelo VAR. Segurança Energética. Dinâmica de Preços.

RESUMEN

La estabilidad de los precios de la electricidad representa un desafío central para las economías dependientes de la energía hidroeléctrica que avanzan hacia transiciones energéticas bajas en carbono bajo variabilidad climática. Este artículo examina los determinantes de los precios de la electricidad en Colombia (2005–2023) utilizando un modelo de Autorregresión Vectorial (VAR) que incorpora precios internacionales del gas natural (Henry Hub), consumo de gas doméstico, niveles de embalses y precios promedio de electricidad. Se aplican Funciones de Respuesta al Impulso (IRF) y Descomposición de la Varianza del Error de Pronóstico (FEVD) para evaluar las interacciones entre factores domésticos y externos, complementadas por pruebas de causalidad de Granger. Los resultados indican que la formación de precios es impulsada predominantemente por factores domésticos; los choques externos producen efectos positivos pero transitorios, disipándose aproximadamente en diez meses. Las condiciones hidrológicas y el consumo de gas doméstico ejercen influencias indirectas moderadas. El mercado eléctrico colombiano muestra resiliencia a corto plazo ante choques externos pero sigue siendo vulnerable a la variabilidad hidrológica impulsada por el clima, lo que subraya la necesidad de diversificar la matriz energética e fortalecer la integración regional.

Palabras clave: Mercado Eléctrico Colombiano. Precios de Electricidad. Modelo VAR. Seguridad Energética. Dinámicas de Precios.

1 INTRODUCTION

The stability and predictability of electricity prices have become central concerns in the global energy agenda, driven by the transition toward low-carbon systems and the growing exposure of power systems to extreme climate events (IEA, 2023a; ECLAC, 2022). Globally, interactions among energy, hydrological, and climatic factors affect market volatility and electricity security (World Bank, 2023), making it essential to understand how these drivers correlate across national and international scales.

In Colombia, this debate is especially relevant given the heavy reliance on hydropower, which supplies around 65% of total generation (UPME, 2025). While hydropower delivers low-carbon benefits, water scarcity episodes force the dispatch of higher-cost thermal plants, raising spot prices and tariff volatility, with direct impacts on consumers and risks to sector financial stability (XM, 2022; CREG, 2023; ECLAC, 2021). Across Latin America, energy transitions are closely tied to security concerns, as electricity systems remain shaped by structural dependence on a limited set of primary sources and continued exposure to price volatility, supply disruptions, and climate risks (Anônimo, 2023; Anônimo *et al.*, 2025)

Natural gas has therefore been framed as a “transition” or “bridge fuel” to support decarbonization while ensuring reliability and price stability. In 2022, it represented about 23% of Colombia’s total energy supply and is widely perceived as a flexible complement to variable renewables (Anônimo *et al.*, 2025). Yet declining domestic reserves and rising import dependence introduce vulnerabilities to external price shocks, geopolitical risks, and infrastructure lock-in, as highlighted by recent disruptions such as COVID-19 and the Russia-Ukraine war (World Bank, 2023; Reuters, 2025). In hydropower-dependent systems, increasing climate variability amplifies this tension: droughts reduce reservoir levels and increase reliance on gas- and coal-fired generation, directly shaping price formation and volatility (Lu *et al.*, 2023; Amwal Al Ghad, 2024; Palma *et al.*, 2024; Yin & Lam, 2025).

Colombia has expanded solar PV, reaching roughly 7% of generation in 2025, but its variability limits security contributions during low inflow periods without large-scale storage (Sustainable Energy Institute, 2025; Cardona-Vasquez *et al.*, 2024). Beyond technology shifts, the transition also requires changes in market design, regulation, planning, and governance, particularly in developing economies where institutional quality and regulatory

predictability are critical (Valkenburg & Cotella, 2016; IEA, 2023b; Icaza-Álvarez *et al.*, 2023; Lin & Zhang, 2025).

Recent work has analyzed generation complementarity in Colombia using VAR and GAM approaches (Joaqui-Barandica *et al.*, 2025), yet a gap remains on the relative impact of domestic versus external factors on electricity price formation amid an evolving energy matrix and rising exposure to climate and fuel-market shocks. Accordingly, this study analyzes the contribution of domestic and international drivers to electricity price formation in Colombia over 2005–2023 by estimating a VAR model and applying impulse response functions and forecast error variance decomposition to trace shocks, their propagation, and their contributions to price dynamics. The article proceeds as follows: Section 2 reviews the Colombian electricity market and evidence on price determinants; Section 3 describes methods and variables; Section 4 discusses results and policy implications; and Section 5 concludes with policy directions.

2 THE COLOMBIAN ELECTRICITY MARKET AND THE DETERMINANTS OF PRICE DYNAMICS

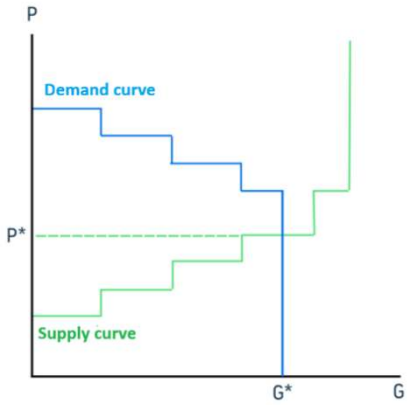
The dynamics of the global electricity market have become central to debates on energy security and the transition toward more efficient and sustainable systems (IEA, 2023; ECLAC, 2022). Greater renewable integration, volatility in international fossil fuel prices, and structural market changes have intensified the interdependence between economic, climatic, and geopolitical drivers. As a result, electricity prices increasingly reflect not only domestic supply–demand balances but also external shocks transmitted through fuel markets, climate variability, and international trade (World Bank, 2023; Lazaro & Serrani, 2023).

In Colombia, electricity price formation is governed by the centralized Wholesale Energy Market (MEM), operated by XM (XM, 2022). Generators—predominantly hydropower producers—submit bids by quantity and price, ranked by variable generation costs and matched with projected demand to determine the market clearing (spot) price (Figure 1), consistent with marginal-cost economic dispatch (Cramton *et al.*, 2005; Botero Duque *et al.*, 2016). This design makes short-term prices highly sensitive to the marginal unit: under normal hydrology, low-variable-cost hydropower tends to set the price, while under hydrological stress higher-cost thermal plants—especially natural gas and coal—become marginal,

driving sharp increases. This provides the rationale for including hydrological indicators and thermal fuel variables in empirical models.

Figure 1

Formation of the market clearing price in the Colombian MEM



Source: Adapted from Botero Duque *et al.* (2016).

Hydrological conditions are a key domestic determinant. With hydropower accounting for roughly 57.5% of generation, reservoir levels and inflows directly influence system costs and volatility, particularly during El Niño events that constrain hydro output and raise reliance on thermal generation (UPME, 2025; Eguiguren-Cosmelli, 2019). Within this dispatch logic, gas-fired plants play a state-dependent role: gas costs are not continuously reflected in prices but materialize when reservoirs are low or demand exceeds hydro availability, so gas functions as a conditional amplifier of volatility (XM, 2022). Accordingly, including gas prices and gas consumption in a VAR is justified: prices capture cost shocks, while consumption proxies thermal dispatch intensity and system stress. Colombia's growing dependence on imported gas also strengthens the transmission of international benchmarks (e.g., Henry Hub) into domestic electricity costs, especially during high thermal dispatch.

Beyond gas, global fossil fuel markets affect Colombian electricity prices through fuel substitution, logistics, and broader macroeconomic channels, as evidenced by shocks linked to COVID-19 and the Russia–Ukraine war (World Bank, 2023; Palma *et al.*, 2024). Domestic pressures—such as supply constraints and delays in expansion projects (e.g., Hidroituango in 2018)—have also contributed to volatility (Eguiguren-Cosmelli, 2019; Muñoz-Santiago *et al.*, 2021). Complementary mechanisms, notably the reliability charge, aim to ensure long-

term adequacy, yet evidence points to a positive correlation with higher spot prices, raising questions about regulatory effectiveness and distributional impacts (Amador *et al.*, 2013; CREG, 2018; XM, 2022; Cramton *et al.*, 2005). Although long-term contracts mitigate exposure to hydrological and spot-price fluctuations, they may not fully accommodate increasing renewable penetration, climate variability, and evolving regulation; under the current framework, greater non-conventional renewables could increase spot volatility, reinforcing the case for institutional reforms (Cardona-Vásquez *et al.*, 2024).

The literature on Colombia has progressed from market liberalization and system operations to forecasting and policy evaluation, using approaches such as ARIMA/IGARCH and multivariate methods (Amador *et al.*, 2013; Cramton *et al.*, 2005; Muñoz-Santiago *et al.*, 2021; Eguiguren-Cosmelli, 2019; Hernández Bueno *et al.*, 2020). More recently, BESS have gained attention as emerging flexibility options following regulatory advances, signalling gradual diversification beyond thermal sources (CREG, 2023; Cardona-Vásquez *et al.*, 2024). Overall, while hydrology remains critical, electricity price formation in Colombia reflects interacting domestic and external factors, and understanding these dynamics is essential for transition strategies that strengthen resilience, energy security, and price stability under climatic and geopolitical uncertainty.

3 RESULTS

3.1 CHARACTERIZATION OF TIME SERIES AND STATIONARITY TESTS

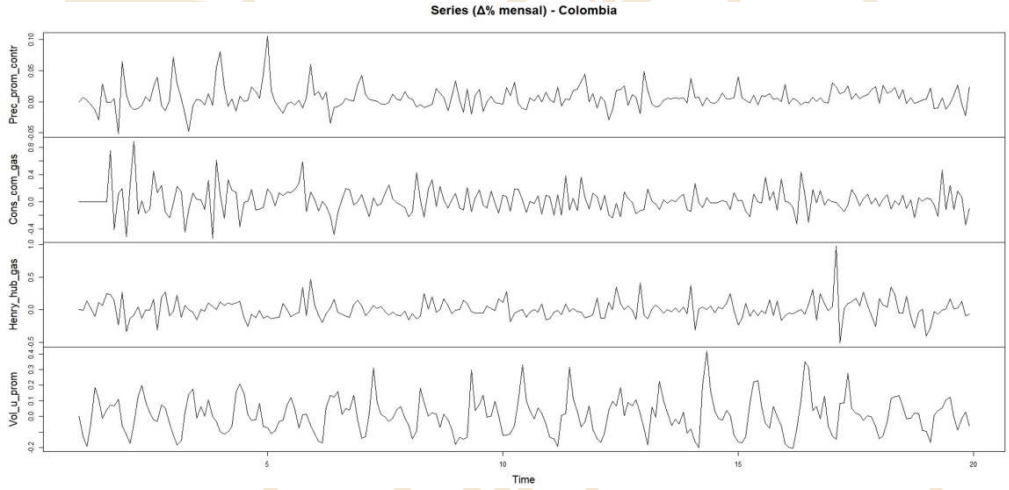
The dataset for the period under analysis consists of monthly observations of four variables that are central to the dynamics of the Colombian electricity system: (i) average usable reservoir storage, (ii) natural gas consumption for power generation, (iii) average electricity contract prices, and (iv) international natural gas prices (Henry Hub). In line with the methodological framework, all series were transformed into monthly percentage changes using relative differences. This transformation standardizes the scale of the variables, removes deterministic trends, and isolates short-term dynamics that are most relevant for the transmission of shocks within the system.

The transformed series display the oscillatory behavior typically expected of percentage variations, as illustrated in Figure 2. Average electricity contract prices exhibit relatively moderate fluctuations, consistent with their role as a partial buffer against spot price

volatility. In contrast, reservoir storage levels show pronounced cyclical patterns linked to hydrological variability and the occurrence of extreme climatic events, such as El Niño episodes. Natural gas consumption presents periods of heightened volatility, reflecting adjustments in thermal dispatch in response to hydrological constraints and system balancing needs. Finally, Henry Hub prices display sharper and more abrupt movements, characteristic of exogenous shocks originating in international fossil fuel markets.

Figure 2

Transformed historical time series



Source: Author's own elaboration.

Table 1 provides a concise summary of the descriptive statistics of the transformed time series. Higher volatility is observed in natural gas consumption and in the Henry Hub price series, reflecting the greater sensitivity of these variables to short-term adjustments in dispatch decisions and to exogenous shocks in international fuel markets. In contrast, electricity contract prices remain relatively stable, consistent with their role in smoothing price fluctuations in the Colombian power market. The usable reservoir storage variable exhibits pronounced variability associated with the strong hydrological cyclicality that characterizes Colombia's electricity system.

Table 1

Descriptive statistics of the transformed series (%)

Variable	Mean	SD	Min	Median	Max
Weighted usable reservoir volume	0.63	11.60	−20.28	0.25	41.95
Natural gas consumption	1.82	19.13	−53.61	0.29	89.22
Electricity contract prices	0.63	1.82	−5.10	0.36	10.45
Henry Hub price	0.72	15.31	−51.03	−0.55	97.42

Source: Author's own elaboration.

The stationarity of the series was assessed using the Augmented Dickey–Fuller (ADF) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests. The ADF statistics are strongly negative, with p-values below the 1% significance level, allowing rejection of the null hypothesis of a unit root. The KPSS test yields low test statistics with p-values close to 0.10, providing insufficient evidence to reject the null hypothesis of stationarity. The consistency between both tests confirms that, after transformation into monthly percentage changes, all series satisfy the stability conditions required for VAR estimation and subsequent dynamic analyses.

3.2 ESTIMATION AND VALIDATION OF THE VAR MODEL

The selection of the optimal lag length was conducted by applying the Akaike Information Criterion (AIC), Hannan-Quinn (HQ), Schwarz Criterion (SC), and Final Prediction Error (FPE) to the series transformed into monthly percentage changes, using the VARselect function in RStudio. The results revealed substantial divergence across criteria: the AIC suggested 12 lags, HQ and SC indicated a single lag, while the FPE recommended three lags. Such discrepancies are typical in highly volatile time series, reflecting the different penalties imposed by each criterion.

Given this divergence, VAR models with 1, 2, 3, and 4 lags were estimated to allow for a comparative assessment of the empirical performance of the candidate specifications. The comparison indicates that the VAR(3) specification delivers the best overall performance, combining dynamic stability, the absence of economically relevant residual autocorrelation, and economic interpretability. A quarterly lag structure is consistent with the dynamics of the Colombian power system: usable reservoir levels are highly sensitive to meteorological conditions, seasonal cycles, and climate phenomena such as El Niño, whose effects tend to

materialize over a three-month horizon. Similarly, the transmission of international natural gas price shocks to thermal generation and domestic gas consumption typically operates with a lag, reinforcing the plausibility of the selected specification.

Once the temporal structure was defined, the VAR(3) model was estimated and subjected to standard diagnostic tests for stability, normality, heteroskedasticity, and residual autocorrelation. All eigenvalues lie strictly within the unit circle, confirming the dynamic stability of the system and ensuring that impulse responses to shocks are convergent. The Portmanteau test suggests the presence of residual autocorrelation ($p = 0.014$); however, this test is known to be highly sensitive in multivariate settings, and the detected dependence is of limited magnitude. This result is consistent with the confirmed stability of the system, the behavior of the impulse response functions, and the statistical coherence of the estimated relationships.

The multivariate ARCH-LM test ($p = 0.4119$) does not reject the null hypothesis of homoskedasticity, indicating stable residual variance, a particularly relevant result in energy market applications, which are often subject to frequent shocks and pronounced volatility. Normality is rejected by the Jarque-Bera test ($p < 2.2 \times 10^{-16}$), a common outcome in energy time series characterized by heavy tails and extreme events. Nonetheless, VAR estimators remain consistent under such conditions, and inference is preserved through robust analytical tools such as impulse response functions (IRFs) and forecast error variance decomposition (FEVD).

Taken together, these results indicate that the VAR(3) model exhibits both statistical consistency and economic coherence. The specification satisfies the core validity requirements, namely stationarity, dynamic stability, and meaningful parameterization. While some ideal assumptions are not fully met, a recurrent feature in empirical studies of energy markets, the overall performance of the model remains robust. The validated VAR thus provides a reliable representation of the interactions between hydrological conditions, thermal generation, and international fuel market dynamics within the Colombian electricity system.

3.3 ELECTRICITY PRICE DYNAMICS IN THE VAR MODEL

The electricity price equation in the VAR framework models monthly changes in average electricity prices as a function of their own lags and the lagged values of the system's

other variables: international natural gas prices (Henry Hub), natural gas consumption for power generation, and average usable reservoir volume, together with seasonal controls. This specification provides an initial view of the model's internal structure prior to assessing multivariate dynamics through impulse response functions.

Regarding external determinants, the Henry Hub price shows a positive and statistically significant effect at the second lag (0.019, **), suggesting that global gas-market shocks transmit to Colombia's average electricity contract prices with an approximate two-month delay. The remaining lags are not significant, implying an episodic rather than persistent transmission within this equation. Gas consumption for power generation is also significant at the second lag (0.016, *), with moderate magnitude, consistent with thermal dispatch dynamics affecting prices within a narrow time window.

By contrast, usable reservoir volume is not significant at any lag. This does not rule out hydrological influence, but it indicates no direct effect in this specific equation. Instead, hydrology likely operates indirectly through dispatch decisions, gas consumption, and shifts in the generation mix, which are better captured by the system's dynamic responses through IRFs and FEVD. Several seasonal terms are also significant, reflecting systematic annual patterns in electricity price behavior linked to demand and hydrological availability.

In summary, the results of this equation reveal statistically significant effects of the Henry Hub price and gas consumption at the second lag, while the remaining coefficients do not exert a robust direct impact on electricity prices. These findings highlight the presence of delayed transmission mechanisms influencing the dependent variable and provide useful insights into the local structure of the VAR model. However, given the multivariate nature of the framework, a comprehensive interpretation of electricity price dynamics requires integrating these results with the broader system-wide interactions captured by the model's dynamic responses.

3.4 IMPACT OF EXTERNAL AND INTERNAL SHOCKS

The impulse response functions (IRFs) illustrate how internal and external shocks propagate over time and affect electricity prices in Colombia. Using orthogonalized shocks, with robustness supported by bootstrap confidence intervals, the IRFs assess the direction, magnitude, and persistence of each variable's effect over a 24-month horizon. As shown in

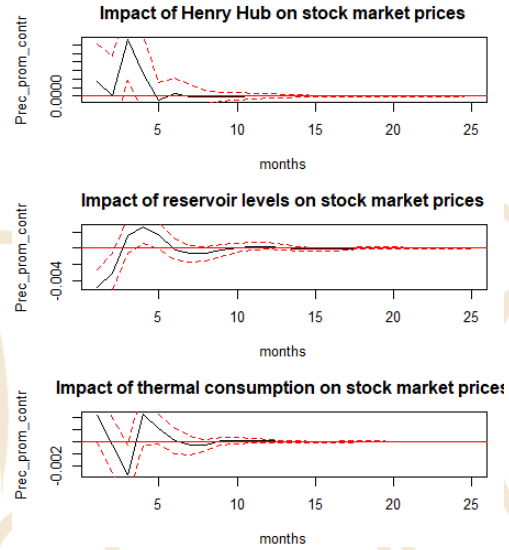
Figure 2, this horizon captures both short-run adjustments and medium-term impacts, revealing differences in transmission speed and price sensitivity across disturbances.

Overall, electricity prices react immediately to shocks, but responses are moderate and short-lived. A shock to international natural gas prices triggers a positive and statistically significant response, peaking around months three to four and fading out before month ten, suggesting a partial and weakly persistent pass-through of international fuel costs. A reservoir-level shock produces an initial negative response (consistent with reduced thermal dispatch under favorable hydrology) followed by a small rebound, but the effect remains limited and quickly converges to zero. Gas consumption shocks exhibit the least stable pattern, alternating in sign and largely remaining within confidence bands, reflecting the multicausal and state-dependent nature of dispatch decisions. A shock to the electricity price itself shows brief overshooting and a return to equilibrium within less than a year, supporting model stability.

Taken together, the IRFs indicate that both external and internal shocks affect electricity prices, but with limited intensity and persistence, consistent with the predominance of domestic drivers. Forecast Error Variance Decomposition (FEVD) reinforces this conclusion: own-price shocks dominate across horizons, declining only gradually as the forecast horizon increases (Figure 3), while other variables contribute marginally. This pattern supports the largely endogenous character of electricity price variation in the Colombian market.

Figure 3

Impulse Response Function (IRF) results



Source: Author's own elaboration.

Extending the forecast horizon to 6–12 months reveals a gradual decline in the contribution of own-price shocks, allowing other determinants to play a more visible role in explaining price variability. Within this interval, the Henry Hub price begins to exert a marginal influence, consistent with the delayed effects observed both in the price equation and in the impulse–response functions. Its contribution remains moderate and stable, indicating that international gas markets are relevant to the system but do not assume a dominant role in electricity price formation.

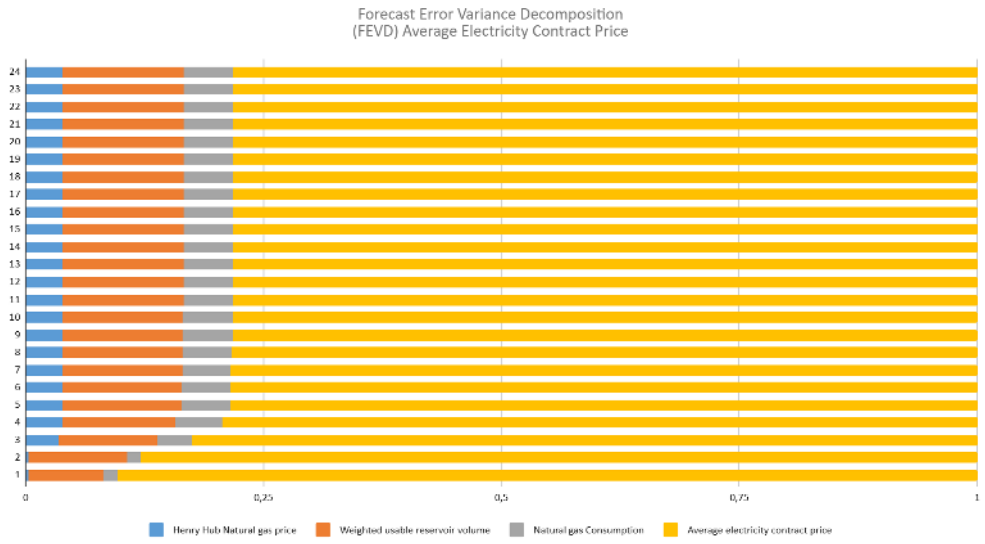
Natural gas consumption for electricity generation also displays a moderate contribution at intermediate horizons, although smaller than that of the Henry Hub price. Its relatively stable share reflects the complementary role of thermal dispatch in price formation, particularly under unfavorable hydrological conditions, while its average explanatory power remains limited. In contrast, reservoir storage levels maintain a low and stable contribution across all horizons, a result consistent with the IRFs and with the estimates obtained in the price equation. This pattern reflects the fact that, although hydrology is structurally important, it does not exert a directly measurable effect when represented by an aggregated monthly average.

At longer horizons (12–24 months), the contributions of the Henry Hub price, gas consumption, and reservoir storage converge toward stable levels, while the electricity price itself continues to be the primary determinant of its own variability. This stability confirms the stationary nature of the system and the progressive dissipation of shocks over time, indicating that the VAR captures dynamics without persistent long-term cumulative effects (Figure 4).

Taken together, the FEVD and IRF results demonstrate that electricity price formation in Colombia is dominated by internal shocks, whereas the transmission of external disturbances remains limited. Natural gas exerts a secondary influence, and thermal generation contributes only marginally, reinforcing the conclusion that price variability is largely governed by endogenous dynamics within the domestic electricity market.

Figure 4

Forecast Error Variance Decomposition (FEVD) results



Source: Author's own elaboration.

3.5 GRANGER CAUSALITY

The Granger causality analysis complements the dynamic assessment provided by the VAR, IRF, and FEVD by testing whether one variable contains additional predictive information about another beyond its own past. The test for international natural gas prices yields a p-value of 0.070, indicating only marginal evidence of Granger causality. This result is consistent with the findings from the other analytical tools and suggests that the influence

of international gas prices on domestic electricity prices is limited. This outcome reflects the dominant role of hydropower generation and the current level of domestic gas production, both of which constrain the transmission of external shocks.

In contrast, reservoir storage levels display more robust statistical evidence of causality. With a p-value of 0.028, the null hypothesis is rejected at the 5% significance level, indicating that hydrological conditions Granger-cause movements in the system. Thus, although reservoir levels do not exhibit statistically significant direct effects in the price equation of the VAR, nor well-defined impulses in the IRFs, both the Granger causality tests and the FEVD reveal that hydrology contains essential information for explaining system variability. In the FEVD, its contribution remains stable and persistent, reflecting the structural role of hydrological conditions in mediating the transition between hydropower and thermal generation technologies. From a sectoral perspective, this result is fully consistent: reservoir levels condition the degree of exposure to thermal dispatch and, consequently, the upward or downward pressure on electricity prices.

Complementarily, natural gas consumption for electricity generation also exhibits strong statistical significance, with a p-value of 0.005. This finding indicates that the intensity of thermal dispatch precedes movements in all system variables, including electricity prices. Such evidence aligns with the operational logic of the Colombian electricity market: during periods of declining reservoir levels, increased reliance on thermal generation raises congestion signals, marginal costs, and fuel use, effects that tend to be reflected subsequently in both average contract prices and spot prices. The fact that gas consumption displays stronger causality than the Henry Hub price reinforces the conclusion that domestic cost conditions (rather than international price signals) are the primary transmitters of shocks in the local market.

These results are consistent with the structural context outlined in the methodology section. Colombia's strong reliance on domestically produced natural gas, combined with recent increases in imports and the ongoing decline in proven reserves, suggests that the system's sensitivity to international gas prices may intensify in the future. Under such circumstances, the robust causality associated with thermal dispatch implies that this mechanism may become an even more relevant channel for shock transmission.

Overall, the Granger causality tests reveal a coherent pattern: hydrological conditions precede system dynamics, thermal dispatch translates these conditions into price signals, and international gas prices exert only a limited influence over the period analyzed. From a methodological standpoint, these findings underscore the importance of interpreting causality jointly with IRF and FEVD results, as statistical significance does not necessarily imply large economic effects. The evidence thus confirms that domestic determinants remain central to electricity price formation in Colombia.

4 DISCUSSION

The results provide an internally consistent view of the determinants of monthly electricity contract price variations in Colombia. Model validation (stationarity, dynamic stability, and joint significance) supports the selected VAR specification as an adequate representation of the joint dynamics among electricity prices, hydrological conditions, thermal generation intensity, and international natural gas prices. Nevertheless, the Colombian electricity market is a complex system shaped by interacting economic signals, regulation, temporal feedback, and segmentation across contract markets, spot markets, regulated charges, and reliability policies; thus, the VAR should be read as a tool to identify dominant drivers of price variability rather than a complete representation of the system. Even so, results consistently indicate that price formation is predominantly domestic, while external shocks exert modest and short-lived effects.

In terms of direct effects, only lagged Henry Hub prices and natural gas consumption are statistically significant in the electricity price equation. These effects are moderate and concentrated on specific delays, implying that international gas price signals are incorporated in a limited and delayed manner. By contrast, neither own-price lags nor hydrological variables show statistically significant direct effects at the monthly frequency, suggesting that their influence operates through broader transmission mechanisms within the system.

Impulse responses reinforce this interpretation: international gas-market shocks generate positive but transitory effects that converge to zero within less than one year, while internal shocks (gas consumption and hydrological conditions) display even weaker or nearly negligible effects on the price path. This rapid dissipation indicates stable dynamics in which disturbances do not generate persistent or cumulative price effects, supporting market

stability and making the VAR framework useful for evaluating resilience in complex electricity markets (Zheng *et al.*, 2026).

Variance decomposition complements these findings. Across horizons, own-price shocks explain the largest share of variability, especially in the short run, evidencing a strong endogenous component. Hydrology and thermal generation maintain persistent—though moderate—contributions over time, reflecting their structural role, while Henry Hub remains low but non-negligible, consistent with limited exposure to imported gas during the sample and hydro dominance. Granger causality tests further clarify temporal precedence: hydrology and gas consumption exhibit clear statistical causality, aligning with the operational logic whereby hydrology conditions renewable availability and thermal dispatch, while Henry Hub shows only marginal causality at the 10% level.

These results must be interpreted against emerging structural trends. Although the influence of international gas prices is limited in-sample, this autonomy may be fragile as declining reserves and rising LNG dependence increase exposure to external volatility and geopolitical risk. Given these conditions, policy priorities should strengthen internal market predictability and hydrological resilience, focusing on improved climate and dispatch forecasting (Lu *et al.*, 2024), investments in green storage and resilience (Le Thanh Ha, 2024), and the integration of flexibility technologies such as BESS and green hydrogen consistent with transition pathways (Vasconcelos and Castilho, 2025). The observed short-term resilience also underscores the macroeconomic value of price stability for fiscal health, inflation control, and growth, consistent with the links between energy security, macro stability, and income outcomes (Mirza *et al.*, 2023; Wang, 2026). Finally, regional energy integration based on renewable complementarities emerges as a viable pathway toward greater autonomy and social stability (Siksnelyte-Butkiene *et al.*, 2025), particularly as renewable transitions may generate new geopolitical tensions (Lin and Zhang, 2025). At the same time, the deployment of technologies such as BESS and solar could reinforce technological dependence via critical mineral supply chains; this strengthens the case for strategies that leverage domestic and regional assets and cooperation to reduce systemic risk in volatile energy markets (Liu *et al.*, 2024; Su *et al.*, 2022). Overall, the combination of statistical, dynamic, and causal evidence confirms the validity of the adopted approach,

identifies key transmission mechanisms, and motivates the subsequent section on policy implications and strategic pathways to strengthen resilience in Colombia and the region.

5 CONCLUSION

The results of this study provide a comprehensive characterization of electricity price formation in Colombia, demonstrating that market dynamics are predominantly shaped by internal determinants, while external shocks (particularly international natural gas prices) exert only modest, transitory, and low-persistence effects. The consistency across the VAR estimates, impulse response functions (IRFs), forecast error variance decomposition (FEVD), and Granger causality tests reinforces this conclusion, indicating that the core transmission mechanisms of the system are fundamentally linked to hydrological conditions, thermal dispatch, and domestic supply-demand interactions.

In light of these mechanisms, it becomes evident that Colombia's relative insulation from international energy price volatility constitutes a source of short-term resilience. However, this apparent autonomy coexists with significant structural vulnerabilities, particularly the strong dependence on hydrology and domestic gas production. The country's growing exposure to the international liquefied natural gas (LNG) market (especially during periods of hydrological stress) introduces geopolitical and operational risks that extend beyond the strictly economic dynamics captured by the model. Potential reliance on gas imports in a context of global price volatility, geopolitical tensions, and increasing competition for liquefaction capacity underscores the need for long-term energy planning that explicitly incorporates adverse and stress scenarios, rather than relying solely on average conditions.

Moreover, the system remains highly sensitive to unfavorable hydrological cycles and to the behavior of thermal dispatch, which functions as the main transmission channel to prices. Policies aimed at diversifying the generation mix, expanding storage capacity, strengthening the domestic gas market, and improving integrated water resource management therefore emerge as central pillars for a robust and resilient energy transition in the Colombian context.

From a regulatory and sectoral perspective, the findings reinforce the importance of orienting public policies toward the internal determinants of the electricity market, enhancing the predictability of climatic cycles, refining investment signals for backup and flexibility

technologies, and strengthening the system's capacity to respond to hydrological stress events. Such measures are essential to preserving price stability and safeguarding energy security amid increasing climate variability.

Within this framework, regional electricity integration emerges as a strategic opportunity to further enhance the resilience of the Colombian system against the identified shocks. Colombia's geographic position within the Colombia–Panama corridor, combined with the hydrological complementarities present in the Central American Electrical Interconnection System (SIEPAC), significantly expands the potential for mitigating internal supply fluctuations. Countries such as Panama and Guatemala (strongly interconnected within the regional system and characterized by hydrological and seasonal regimes distinct from Colombia's) could serve as alternative sources of flexibility. This climatic and operational heterogeneity strengthens the feasibility of cross-border energy exchange mechanisms that not only smooth short-term variations but also reduce the structural exposure of the Colombian system to domestic hydrological volatility and growing dependence on fossil fuels during critical periods.

Although the VAR model is subject to limitations associated with monthly data frequency and the inability to fully represent the institutional architecture of the sector, its application provides a coherent and robust interpretation of the main transmission mechanisms and sources of price variability. As such, it contributes meaningfully to a deeper understanding of the functioning of the Colombian electricity market.

Finally, beyond its methodological contributions, this analysis provides relevant insights for understanding electricity price dynamics as an integral component of the energy transition under increasing climate variability. In hydro-dominated systems such as Colombia's, prices function not only as market outcomes, but also as signals of climate exposure, system flexibility, and transition readiness. The predominance of domestic determinants, particularly hydrology and thermal dispatch, indicates that price variability is closely tied to climate conditions and to the availability of low-carbon flexibility options. As climate change intensifies hydrological uncertainty, electricity prices are likely to become an increasingly important channel through which climate risks are transmitted to consumers and investors. In this context, strengthening renewable diversification, storage capacity, demand-side flexibility, and regional interconnections becomes essential not only for decarbonization,

but also for price stability and energy security. Thus, understanding price formation under climate stress is central to designing energy transition pathways that are not only low-carbon, but also resilient, affordable, and socially sustainable.

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