Article

Explaining Mexico's Energy–Economy Linkages under Limited Information: VAR-Based IRF and FEVD Evidence

Juan A. Moreno-Hernández [1]*, Margarita De la Portilla-Reynoso [2], Roberto C. Moreno-Hernández [3]*, Claudia del C. Gutiérrez-Torres [4], Juan G. Barbosa-Saldaña [5], Didier Samayoa-Ochoa [6], José A. Jiménez-Bernal [7]

[1] Escuela Superior de Ingeniería Mecánica y Eléctrica, Instituto Politécnico Nacional, Mexico City, Mexico; jmorenoh1800@egresado.ipn.mx
[2] Escuela Superior en Economía, Instituto Politécnico Nacional, Mexico City, Mexico; mdelaportillar2100@alumno.ipn.mx
[3] División de Geociencias Aplicadas, Instituto Potosino de Investigación Científica y Tecnológica A.C., San Luis Potosí, Mexico; roberto.moreno@ipicyt.edu.mx
[4] Escuela Superior de Ingeniería Mecánica y Eléctrica, Instituto Politécnico Nacional, Mexico City, Mexico; cgutierrezt@ipn.mx
[5] Escuela Superior de Ingeniería Mecánica y Eléctrica, Instituto Politécnico Nacional, Mexico City, Mexico; jbarbosas@ipn.mx
[6] Escuela Superior de Ingeniería Mecánica y Eléctrica, Instituto Politécnico Nacional, Mexico City, Mexico; dsamayoa@ipn.mx
[7] Escuela Superior de Ingeniería Mecánica y Eléctrica, Instituto Politécnico Nacional, Mexico City, Mexico; jjimenezb@ipn.mx
* Correspondence: jmorenoh1800@egresado.ipn.mx (J.A.M.), roberto.moreno@ipicyt.edu.mx (R.C.M.)

Abstract: This study examines the dynamic modeling framework to examine the short- and medium-linkages between Mexico's economy and energy system under conditions of limited information. Using a vector autoregression (VAR) formulation, nine interdependent macroeconomic and energy variables are jointly analyzed: gross domestic product (GDP), oil rents, crude oil prices, crude oil production, total energy consumption, coal-fired electricity generation, installed renewable capacity, public expenditure, and CO_2 emissions. All variables were standardized and tested for stationarity using Augmented Dickey–Fuller (ADF) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) procedures before estimating a stable VAR with optimal lag selection and residual diagnostics. Dynamic system responses were simulated through impulse response functions (IRFs), generalized IRFs (GIRFs), and forecast error variance decomposition (FEVD), complemented by Granger causality tests to assess directional dependencies and feedback effects. The results reveal that oil rents exert a persistent positive influence on GDP and fiscal expenditure, reinforcing Mexico's fiscal dependence on hydrocarbons. Coal-based generation negatively affects output while contributing to higher emissions. Energy consumption promotes short-term growth, whereas renewable capacity remains pro-cyclical and weakly integrated with macroeconomic performance. FEVD outcomes show that GDP and renewable capacity are primarily self-driven, while oil prices, production, and emissions exhibit strong mutual dependencies. Overall, the findings portray a fiscally and environmentally constrained energy–economy system still dominated by hydrocarbons. Strengthening PEMEX operational efficiency, accelerating fiscal diversification, and implementing institutional reforms to attract renewable investment are identified as critical measures to support Mexico's sustainable energy transition.

Keywords: Energy–economy system; Mexico; vector autoregression (VAR); impulse response functions (IRF); forecast error variance decomposition (FEVD); oil rents; PEMEX; renewable energy; CO_2 emissions; energy transition; fiscal dependence

Received:
Revised:
Accepted:
Published:

Citation: Lastname, F., Lastname, F., & Lastname, F. (2025). Mexico's Energy–Economy Linkages: VAR Analysis. *Economies*, *1*(1), 0. https://doi.org/

1. Introduction

The global energy system is undergoing a structural transformation driven by climate commitments, rapid cost declines in renewable technologies, and the imperative to reduce hydrocarbon dependence (Hamilton, 1983). This transition is reshaping energy markets and fiscal architectures worldwide, with particularly profound implications for emerging economies where fossil fuel rents have historically underpinned public finances and economic growth. Mexico represents a paradigmatic case: Petróleos Mexicanos (PEMEX), the state-owned oil company, has long served as both a pillar of development and a source of fiscal vulnerability. Despite periods of high crude prices and production booms, PEMEX has faced recurrent crises associated with heavy fiscal burdens, underinvestment, and high debt, alongside repeated government support (OECD, 2024; IMF, 2024; NRGI, 2025). These structural weaknesses are increasingly exposed as renewable energy expands and hydrocarbon revenues decline, challenging the resilience of Mexico's energy–economy system.

A vast literature has examined energy–economy linkages using econometric approaches such as vector autoregression (VAR), which allow quantifying dynamic feedbacks and propagation effects within complex systems. Studies have explored topics ranging from the impact of oil price shocks on economic performance (Hamilton, 1983) to the role of exchange rates and fiscal policy in energy inflation (Kousar et al., 2022) and the interaction between energy security and sustainable finance (Orzechowski and Bombol, 2022). While findings differ across contexts, a consistent insight is that hydrocarbon dependence persists as a major constraint to sustainable growth. Yet, for Mexico, empirical assessments integrating oil rents, fiscal policy, renewable capacity, and environmental outcomes remain scarce, limiting our understanding of the country's transition pathways.

In response, this study develops a data-driven dynamic modeling framework based on a vector autoregression (VAR) to analyze the short- and medium-term interactions between Mexico's economy and energy system. Nine interrelated variables—GDP, oil rents, oil prices, crude oil production, energy consumption, coal-fired electricity generation, renewable capacity, public expenditure, and CO_2 emissions—are examined using impulse response functions (IRFs) and forecast error variance decomposition (FEVD). This approach enables simulation of how shocks in the energy subsystem propagate across fiscal and environmental dimensions, revealing the structure of feedback mechanisms within the coupled system. The results indicate that (i) oil rents remain central to GDP and fiscal performance, (ii) renewable energy is expanding but remains weakly integrated into macroeconomic activity, and (iii) emissions and coal-fired generation continue to shape Mexico's environmental trajectory. These findings highlight the need for fiscal diversification, enhanced PEMEX efficiency, and institutional reforms to accelerate renewable investment and support a sustainable energy transition.

2. Literature Review

Research on energy–economy linkages using vector autoregressive (VAR) and related models consistently finds that fossil-related shocks exert strong and persistent effects on macroeconomic and price dynamics. In emerging economies, Kousar et al. (2022) show that exchange rate fluctuations and twin fiscal deficits transmit significantly into energy inflation, with long-run relationships confirmed through VAR/VECM estimations and generalized impulse responses that mitigate ordering bias. Their findings emphasize how macro-fiscal imbalances amplify energy price volatility—an insight directly relevant to Mexico's oil-dependent fiscal structure.

A complementary line of research highlights the role of financial channels in shaping energy security. Orzechowski and Bombol (2022) employ a VAR with Granger causality, impulse response functions (IRFs), and forecast error variance decomposition (FEVD) to examine co-movements between green bond markets, sustainability indices, and crude oil prices as proxies for energy security. They reveal predictive interdependence between sustainable finance and energy variables, suggesting that mature green finance ecosystems can buffer transition shocks—an important consideration for economies where public budgets and state-owned enterprises dominate energy investment.

Studies on resource-dependent economies further document how oil price shocks permeate income, fiscal balances, and external accounts. Mukhtarov et al. (2021) estimate a structural VAR (SVAR) for Azerbaijan and show that positive oil price shocks increase GDP per capita and trade turnover while appreciating the domestic currency. Their structural identification provides a robustness layer to reduced-form VARs by imposing theoretically consistent restrictions, a strategy that informs the interpretation of Mexico's oil-linked transmission channels.

For Latin America, panel-based approaches highlight shared regional dynamics. Koengkan, Fuinhas, and Marques (2019) apply a panel VAR (PVAR) to 21 Latin American and Caribbean countries, reporting a bidirectional relationship between energy consumption and economic growth, along with a unidirectional effect from urbanization to energy use. These results reveal persistent demand-side pressures driven by structural transformation, implying that fossil fuel dependence may persist in the absence of accelerated renewable adoption.

Beyond energy quantities and prices, recent research has underscored the role of uncertainty. Using a time-varying parameter VAR (TVP-VAR) for Brazil, Chile, Colombia, Mexico, and major trading partners, Marín-Rodríguez, Pereira, and Gómez (2025) document evolving spillovers from economic policy uncertainty (EPU), showing that connectedness across economies is state-dependent and changes through time. Their results justify reporting IRFs and FEVD across multiple horizons and motivate sensitivity analyses under alternative regimes.

Across these strands, three common insights emerge: (i) oil and macro-fiscal variables shape both energy prices and economic performance; (ii) financial channels interact with energy security and policy transmission; and (iii) dynamic relationships are inherently time-varying and state-dependent. Yet, a significant gap remains for Mexico: few studies integrate oil rents, public expenditure, production and price shocks, renewable capacity, and environmental outcomes within a unified, reproducible dynamic system.

Building on this gap, the present study advances the literature by developing a **robust, system-oriented VAR pipeline** that combines econometric rigor with modern modeling practices inspired by machine learning. Specifically, our framework integrates standardized data preprocessing (frequency harmonization, normalization, and cross-validation), systematic lag and stability diagnostics, and reproducible estimation scripts to ensure transparency and replicability. The model jointly analyzes macroeconomic indicators (GDP, public expenditure, oil rents, exchange rates) and energy–environmental variables (crude oil prices, crude production, energy consumption, coal-fired generation, renewable capacity, and CO_2 emissions).

In contrast with previous VAR applications in *Energies or Ecomomies* and related journals, this approach adopts a modular and iterative workflow analogous to those used in machine learning systems—emphasizing data quality assurance, pipeline reproducibility, diagnostic feedback, and model validation. By integrating impulse response functions (IRFs), generalized IRFs (GIRFs), Granger causality, and forecast error variance decomposition (FEVD), the framework quantifies not only the direction and persistence of shocks but also their systemic propagation and relative importance. This dynamic modeling architecture thus bridges econometric analysis and computational energy system modeling, offering a replicable methodological contribution for studying fiscal, environmental, and technological dependencies in emerging energy economies.

The following section presents the dataset and econometric methodology in detail.

3. Data and Methodology

3.1. Data Sources

The study builds on an integrated multivariate dataset that captures the coupled dynamics of Mexico's macroeconomic, energy, and environmental subsystems. The original database combines *annual* and *monthly* observations; therefore, all series were harmonized to a common monthly frequency using documented, rule-based procedures to address the limited-information setting (i.e., short samples and mixed frequencies). Specifically, temporal alignment preserves levels and trends by applying simple, defensible heuristics consistent with each series' nature (e.g., carry-forward for stock-type indicators and proportional or piecewise-linear interpolation for flow-type indicators), while keeping annual totals intact when applicable. The variables include: gross domestic product (GDP), oil rents as a share of GDP, crude oil prices (Mexican export blend, USD/barrel), crude oil production (thousand barrels per day), total primary energy consumption (kg of oil equivalent per capita), coal-based electricity generation (GWh), installed renewable energy capacity (MW), public expenditure, and CO_2 emissions (Mt).

All variables were sourced from official and internationally recognized repositories to ensure consistency and traceability of the energy–economy system. Primary data were obtained from the World Bank's World Development Indicators (WDI) (World Bank, 2025), Mexico's Secretariat of Energy (SENER, 2025), PEMEX Statistical Yearbooks (PEMEX, 2025), and the International Energy Agency (IEA, 2025). Complementary macroeconomic indicators were collected from INEGI (2025) and Banco de México (Banxico, 2025). All data are publicly available; accession identifiers and direct links are provided in the Supplementary Materials to guarantee full reproducibility.

3.2. Preprocessing

Prior to estimation, all variables were harmonized to a consistent temporal resolution to ensure coherence across the coupled energy–economy–environment system. Each time series was log-transformed where appropriate and standardized to enhance cross-variable comparability and numerical stability during model estimation. Missing observations were reconstructed through interpolation and subsequently cross-validated against independent data sources to preserve the physical and economic consistency of the system.

Stationarity and temporal stability were assessed using Augmented Dickey–Fuller (ADF) (Dickey and Fuller, 1979) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests (Kwiatkowski et al., 1992). When non-stationary behavior was detected, the corresponding series were differenced following standard signal-conditioning practices (Phillips and Perron, 1988) to obtain stable dynamic relationships.

We deliberately exclude cointegration procedures (Engle and Granger, 1987; Johansen, 1991) because our interest lies in short- to medium-run propagation, not long-run equilibria. Inference for impulse responses in VARs with integrated variables remains valid without explicitly modeling cointegration (Sims, Stock, and Watson, 1990). For near-term dynamics, reduced-form VARs with GIRFs/IRFs offer an appropriate identification-light design (Stock and Watson, 2001; Kilian and Lütkepohl, 2017). Therefore, the empirical design emphasizes a stationary VAR formulation to capture near-term transmission mechanisms and short-run system feedbacks.

3.3. Model Specification

To represent the short-term feedback structure of Mexico's energy–economy system, a vector autoregressive (VAR) model was implemented as the core dynamic simulation framework. The VAR approach allows all variables within the coupled system to evolve endogenously, capturing reciprocal interactions and propagation effects among macroeconomic, energy, and environmental components.

The optimal model order (p) was determined through standard information criteria—the Akaike Information Criterion (AIC) (Akaike, 1974), Schwarz Bayesian Criterion (BIC) (Schwarz, 1978), and Hannan–Quinn Criterion (HQ) (Hannan and Quinn, 1979)—supported by robustness checks across alternative lag structures. Model stability was verified using eigenvalue spectrum analysis, ensuring that all characteristic roots lie within the unit circle. Diagnostic tests confirmed the absence of residual autocorrelation and heteroskedasticity, validating the internal coherence of the dynamic system representation.

3.4. Impulse Response Functions and Forecast Error Variance Decomposition

Impulse response functions (IRFs) were employed to simulate the dynamic propagation of perturbations across the coupled energy–economy system. Each one-standard-deviation shock to a variable was traced through time to quantify its transient and persistent effects on the rest of the system. In addition to conventional orthogonalized IRFs (Blanchard and Quah, 1989; Uhlig, 2005), generalized impulse response functions (GIRFs) (Pesaran and Shin, 1998; Koop, Pesaran, and Potter, 1996) were computed to ensure robustness to variable ordering, providing a more invariant mapping of dynamic responses.

Forecast error variance decomposition (FEVD) complements this analysis by decomposing the forecast uncertainty of each subsystem into the proportion attributable to shocks in others (Kilian and Lütkepohl, 2017). This allows evaluating the relative influence and dependency structure among macroeconomic, energy, and environmental components over short-, and medium-term horizons. Together, IRFs and FEVD constitute a dynamic influence mapping framework that captures the direction, magnitude, and persistence of interdependencies within Mexico's energy–economy system.

3.5. Granger Causality Tests

Pairwise Granger causality tests (Granger, 1969) were applied as an additional layer of dynamic diagnostics to identify the directional flow of information among variables. This procedure complements the VAR-based impulse analysis by statistically verifying whether temporal changes in one subsystem systematically precede and predict those in another. The results strengthen the interpretation of dynamic linkages and feedback mechanisms underlying the modeled energy–economy interactions.

3.6. Mathematical Framework of the VAR Model

The mathematical formulation of the vector autoregressive (VAR) model provides the formal representation of the feedback dynamics described above. It expresses how each component of the energy–economy system evolves as a function of its own past states and those of other subsystems.

A vector autoregression of order p, VAR(p), can be written as:

$$Y_t = c + A_1 Y_{t-1} + A_2 Y_{t-2} + \cdots + A_p Y_{t-p} + \varepsilon_t, \tag{1}$$

where Y_t is a $(k \times 1)$ vector of endogenous variables, c is a $(k \times 1)$ vector of intercepts, A_i are $(k \times k)$ coefficient matrices, and ε_t is a vector of white-noise errors with covariance matrix Σ.

3.6.1. Generalized Impulse Response Functions (GIRFs)

While orthogonalized IRFs depend on the ordering of variables through the Cholesky decomposition, generalized impulse response functions (GIRFs) provide order-invariant responses. Following Pesaran and Shin (1998), the GIRF of variable i to a one-standard-deviation shock in variable j at horizon h is defined as:

$$GIRF_{ij}(h) = \mathbb{E}[Y_{i,t+h} \,|\, \varepsilon_{j,t} = \sigma_{jj}^{1/2}, \Omega_{t-1}] - \mathbb{E}[Y_{i,t+h} \,|\, \Omega_{t-1}], \tag{2}$$

where Ω_{t-1} denotes the information set available up to time $t-1$, and $\sigma_{jj}^{1/2}$ is the standard deviation of the innovation to variable j. By construction, GIRFs take into account the observed correlations among innovations and thus do not rely on an arbitrary ordering of the system. This makes them particularly suitable for robustness analysis in VAR applications.

3.6.2. Impulse Response Functions (IRFs)

The moving average representation of the VAR allows tracing the effect of a one-standard-deviation shock to variable j on variable i at horizon h:

$$IRF_{ij}(h) = \frac{\partial Y_{i,t+h}}{\partial \varepsilon_{j,t}}. \tag{3}$$

Orthogonalized IRFs are obtained by Cholesky decomposition of Σ (Blanchard and Quah, 1989), while sign-restricted approaches offer an alternative identification (Uhlig, 2005). In addition, generalized IRFs (Pesaran and Shin, 1998) and nonlinear extensions (Koop, Pesaran, and Potter, 1996) are frequently employed to ensure robustness to ordering assumptions.

3.6.3. Forecast Error Variance Decomposition (FEVD)

FEVD quantifies the proportion of the forecast error variance of variable i attributable to shocks in variable j at horizon h:

$$FEVD_{ij}(h) = \frac{\mathrm{Var}\left(\sum_{s=0}^{h} \Psi_{is}\varepsilon_{j,t-s}\right)}{\mathrm{Var}\left(Y_{i,t+h} - \hat{Y}_{i,t+h}\right)}, \tag{4}$$

where Ψ_{is} are the moving average coefficients. FEVD thus indicates the relative importance of each variable in explaining others over different time horizons (Kilian and Lütkepohl, 2017).

3.7. Software and Reproducibility

All analyses were conducted in Python using open-source libraries (`statsmodels`, `pandas`, `matplotlib`). The complete preprocessing and estimation code is provided in the Supplementary Materials and will be made available via a public repository (GitHub) upon publication, ensuring full reproducibility (see Data Availability).

3.8. Methodological framework

Figure 2 presents an integrated view of the methodological framework, linking the empirical specification of the VAR model with the analytical instruments employed to trace dynamic interconnections within Mexico's energy–economy system.

The subsequent section (Results) operationalizes these methodological components, translating the VAR-based dynamic responses into interpretable economic and energy effects. This enables a system-level understanding of how exogenous shocks propagate through Mexico's coupled fiscal and energy domains, offering quantitative insight into the country's structural dependence on hydrocarbons and the scope for transition dynamics. 252 253

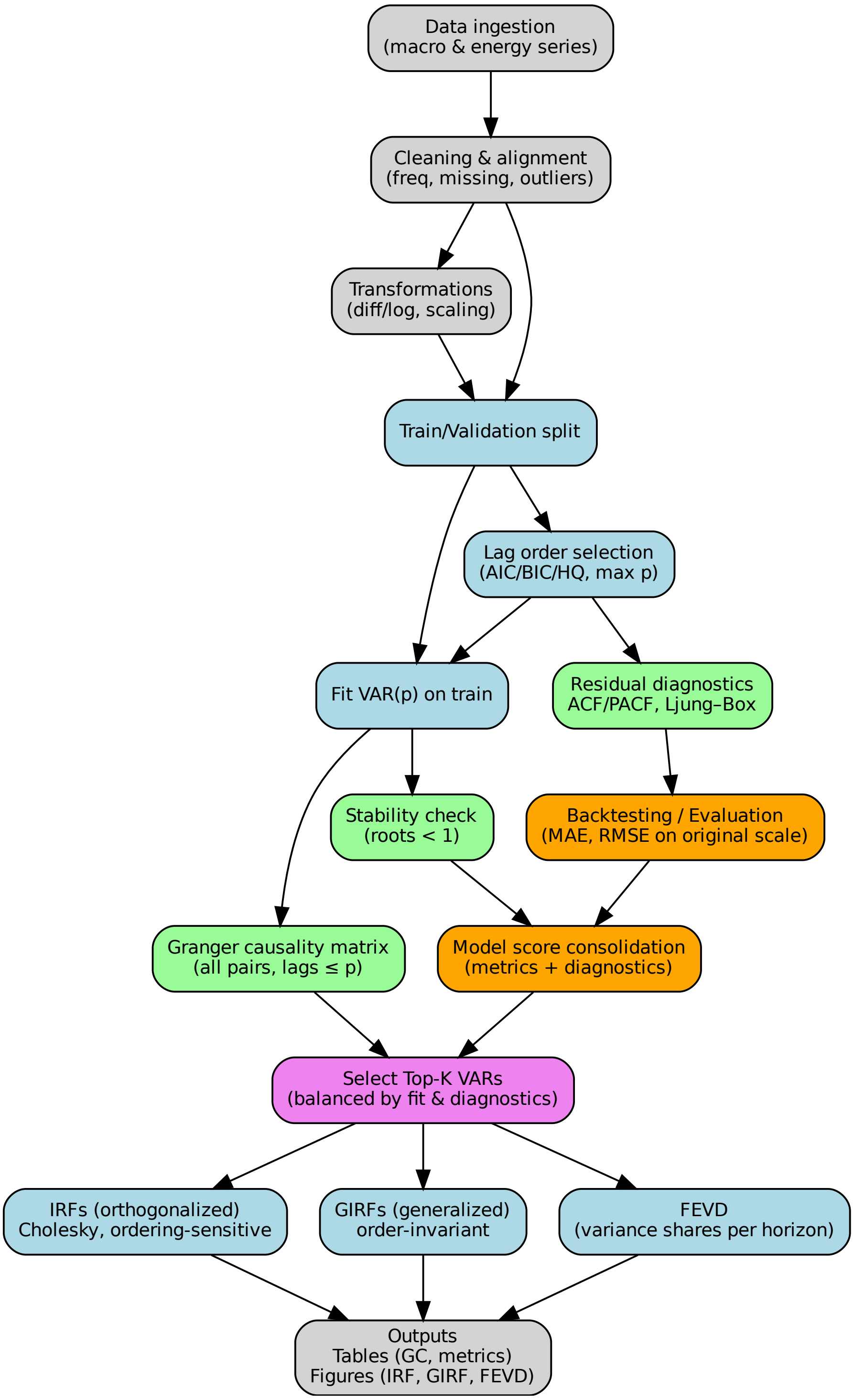

Figure 1. Integrated modeling workflow adopted for the VAR-based simulation of Mexico's energy–economy system. The framework links data harmonization, system calibration, diagnostic assessment, and dynamic propagation analysis (IRF, GIRF, FEVD), illustrating the feedback-oriented structure of the empirical model.

4. Results

4.1. Generalized Impulse Response Functions (GIRFs)

Generalized impulse response functions (GIRFs), which are invariant to variable ordering, are presented as the primary dynamic evidence from the estimated VAR model. Figures 2–3 illustrate the GIRFs over a 40-day horizon. The results indicate that oil rents and energy consumption exert a positive and statistically significant impact on GDP, whereas shocks to coal-fired generation (CGEN) and oil prices (MXOP) have a negative effect on economic growth.

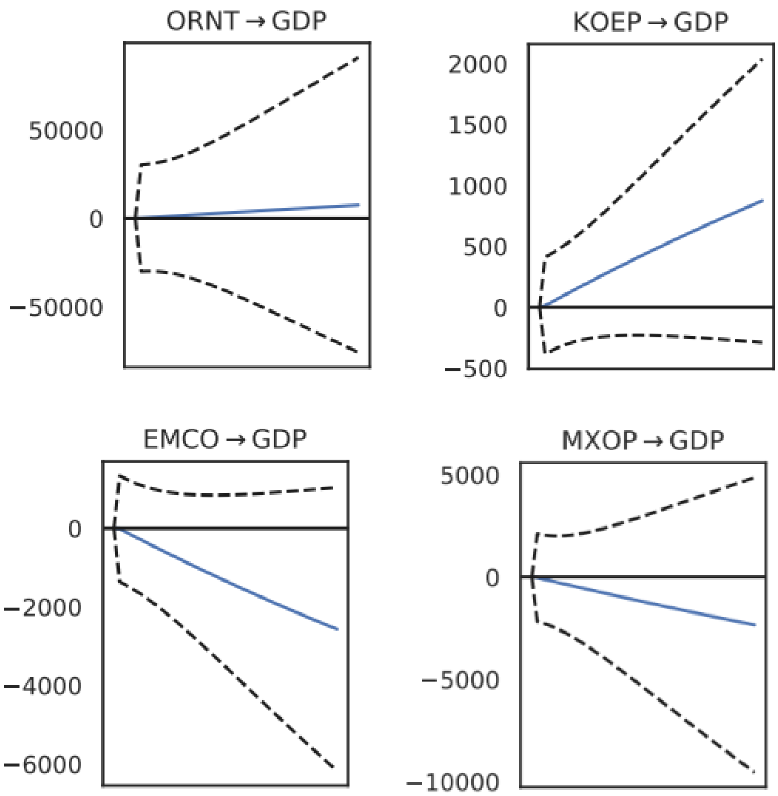

Figure 2. Generalized impulse responses of GDP to shocks in selected variables.

Renewable capacity (RCAP) expands in tandem with GDP but exerts only a marginal autonomous effect, reflecting its reliance on revenues generated from fossil fuels. CO_2 emissions respond positively to shocks in oil rents, crude oil production, energy consumption, and fossil-based generation, underscoring the persistence of a carbon-intensive system. These patterns align with theoretical expectations and emphasize the asymmetric role of hydrocarbons as systemic drivers, with electricity generation and emissions functioning primarily as outcomes.

Finally, the Mexican crude oil price emerges as a key determinant of GDP dynamics. If PEMEX fails to reduce operational costs, an increase in the export blend price transmits negatively to GDP, weakening the economy's growth cycle: savings $\rightarrow$ investment $\rightarrow$ capital accumulation rates $\rightarrow$ production $\rightarrow$ wages $\rightarrow$ economic growth (GDP). The complete set of impulse–response results is provided in Appendices A and B.

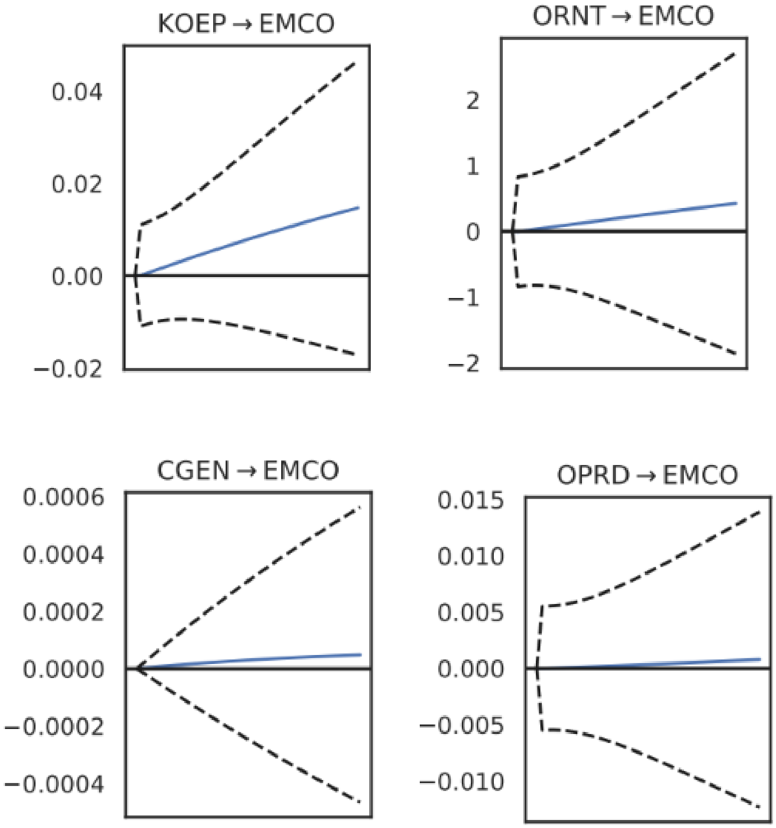

Figure 3. Generalized impulse responses of CO_2 emissions to shocks in selected variables.

4.2. Impulse Response Functions (IRFs): Validation

Orthogonal impulse response functions (IRFs), estimated through a Cholesky decomposition, are computed to provide a benchmark for comparison with the generalized IRFs (GIRFs). Although orthogonal IRFs are sensitive to variable ordering, the results broadly corroborate the GIRF evidence: GDP responds positively to oil rents and energy consumption, but negatively to coal-fired generation and oil price shocks. Similarly, CO_2 emissions rise following fossil-related shocks. The convergence between GIRFs and orthogonal IRFs reinforces the robustness of the findings, as summarized in Table 1, which reports the sign and magnitude of key responses at horizon $h = 40$.

Table 1. Comparison of IRF and GIRF responses at horizon $h = 40$.

Shock → Response	**IRF (sign)**	**GIRF (magnitude)**
Oil Rents → GDP	Positive	+7,613
Energy use → GDP	Positive	+875
Coal-fired gross electricity generation → GDP	Negative	-7.0
Mexican crude export blend price → GDP	Negative	-2,339
GDP → Renewable installed capacity	Positive	+0.0000169
Oil Rents → CO_2	Positive	+0.424
Coal-fired gross electricity generation→ CO_2	Positive	+0.000048
Energy use→ CO_2	Positive	+0.0147
Government expenditure → CO_2	Positive	-0.0000005 (= 0)

4.3. Forecast Error Variance Decomposition (FEVD)

The forecast error variance decomposition (FEVD) (Kilian and Lütkepohl, 2017) assesses the relative importance of each variable in explaining the prediction errors of others, distinguishing between short-, and medium- effects. The results reveal heterogeneous patterns of interdependence within Mexico's energy–economy system.

GDP exhibits a variance explained almost entirely by its own shocks, reflecting strong inertia and the self-referential nature of its macroeconomic dynamics throughout the model horizon. Similarly, renewable energy capacity (RCAP) and energy consumption (KOEP) are predominantly driven by their own shocks, indicating limited impulse transmission to or from the rest of the system.

By contrast, CO_2 emissions display a high proportion of variance explained by shocks to energy consumption and coal-fired generation (CGEN), consistent with Mexico's energy matrix remaining heavily fossil-based. Public expenditure (GEXP), although self-driven in the short term, becomes increasingly influenced by GDP and oil rents at medium horizons, underscoring the dependence of fiscal stability on energy-related revenues.

Coal-fired generation evolves from being primarily explained by its own shocks in the short term to being increasingly influenced by emissions and energy consumption in the long run, reflecting its intermediate role in the energy–environment transmission channel. Crude oil production (OPRD), while largely self-driven in the short term, shows long-run contributions from oil prices (MXOP) and emissions, highlighting the interplay between market dynamics, production, and environmental outcomes.

The Mexican oil price (MXOP) and oil rents (ORNT) display more balanced interactions: oil rents combine own shocks with influences from GDP and oil prices, reflecting their role as a bridge between the real economy and hydrocarbon dynamics. Oil prices, in turn, are not explained solely by their own shocks but also reflect feedback from production and oil rents, consistent with the structurally integrated nature of the sector.

Overall, the FEVD confirms that while certain variables (GDP, renewable capacity, and energy consumption) follow strongly self-referential dynamics, others (CO_2 emissions, coal-fired generation, oil prices, crude oil production, and oil rents) exhibit significant interdependence (see Figure 4). These results underscore the persistence of fossil fuel dependence and the need for renewable capacity to evolve toward deeper integration with Mexico's national energy and economic system. The complete set of FEVD charts is provided in Appendix C.

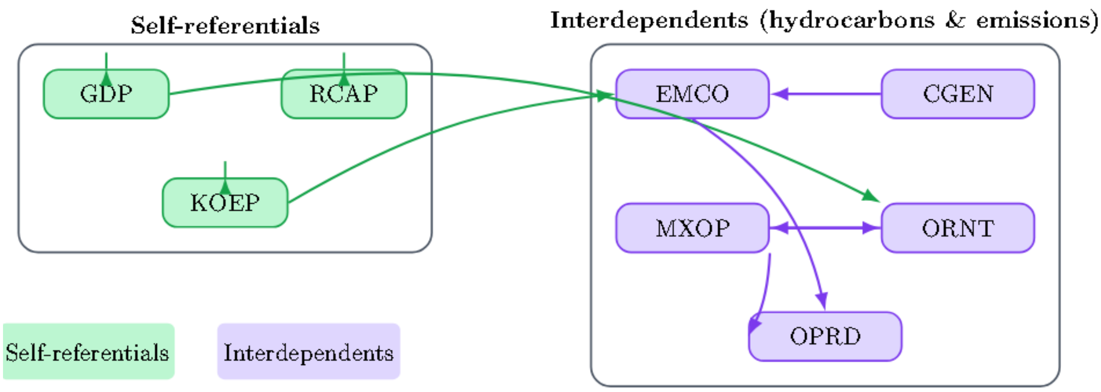

Figure 4. Conceptual map of FEVD interrelations in Mexico. Variables are coded as self-referential (green) or interdependent (purple).

4.4. Granger Causality and Robustness Checks

Pairwise Granger causality tests provide additional evidence on directional relationships (Granger, 1969). The results confirm that coal-fired generation functions primarily as a systemic receptor, dependent on virtually all other variables, while emissions predominantly reflect shocks from hydrocarbons, energy consumption, and fiscal expenditure. Additional linkages of interest include the direct relationship coal-fired generation →

CO_2 and the weak feedback coal-fired generation $\rightarrow$ Renewables, suggesting that fossil infrastructure constrains renewable expansion trajectories. Moreover, the fiscal–energy transmission channel is evident in the relationship Public Expenditure $\rightarrow$ Oil Price, underscoring the role of fiscal policy as a propagation mechanism within the oil cycle.

Robustness checks using generalized IRFs (GIRFs) confirm that the main patterns hold regardless of variable ordering. In both orthogonal IRFs and GIRFs, oil rents, energy consumption, and hydrocarbon production exert a positive and statistically significant effect on GDP, while coal-fired generation and oil price shocks negatively affect economic growth. Similarly, the positive association between oil rents and CO_2 emissions, as well as the role of energy consumption in increasing carbon intensity, remain consistent across methodologies. Minor differences in magnitude indicate some sensitivity to identification: the links between GDP and renewable capacity, and between coal-fired generation and emissions, appear weaker in GIRFs, while the impact of public expenditure on CO_2 is attenuated. These variations do not alter the overall direction of the results but highlight the importance of combining IRFs with GIRFs to ensure robustness. Stability analysis further verifies that all eigenvalues lie within the unit circle, confirming the reliability of the VAR specification.

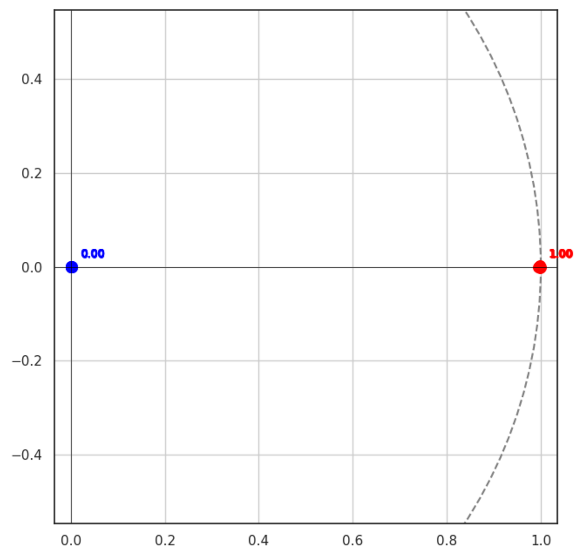

Figure 5. Stability check of the estimated VAR model (all roots inside unit circle).

5. Discussion

The results of the VAR analysis—supported by impulse response functions (IRFs), forecast error variance decomposition (FEVD), Granger causality tests, and generalized IRFs (GIRFs)—confirm Mexico's structural dependence on the hydrocarbon sector. Oil rents exert a persistent positive influence on GDP growth, while renewable energy capacity has yet to generate an autonomous or significant contribution to economic performance. The vulnerability of GDP to oil price shocks further underscores the need for PEMEX to modernize its cost structure and improve operational efficiency.

Granger causality tests reinforce these findings: hydrocarbons and fiscal policy emerge as key predictive drivers, whereas coal-fired generation and CO_2 emissions act predominantly as receivers of systemic shocks. GIRF analysis corroborates the main patterns identified through orthogonal IRFs, showing that oil rents, energy consumption, and hydrocarbon production contribute positively to GDP, while coal-fired generation and oil prices exert negative effects. Differences in magnitude across methods suggest sensitivity in certain relationships—such as GDP–renewables and coal–emissions—but the overall conclusions remain consistent. Collectively, these results highlight both the resilience and fragility of Mexico's energy–economy system.

5.1. Comparison with Previous Studies

Our findings align with and extend earlier VAR-based studies of energy–economy linkages. Kousar et al. (2022) demonstrate how exchange rate dynamics and fiscal deficits amplify energy inflation, underscoring the role of macroeconomic structures. Similarly, Orzechowski and Bombol (2022) show that financial instruments such as green bonds are critical for sustaining energy security. Focusing on Azerbaijan, Mukhtarov et al. (2021) report that oil price shocks are central determinants of macroeconomic performance, shaping both exchange rates and external balances.

In comparison, the Mexican experience reveals a distinct pattern: oil rents function not only as a source of vulnerability but also as the main enabler of fiscal and energy investments. The IRF, FEVD, and Granger evidence suggests that although renewable capacity is positively linked to growth, its reliance on oil-derived revenues creates a feedback loop that delays Mexico's decoupling from hydrocarbons. Generalized impulse response functions, as proposed by Pesaran and Shin (1998), confirm the robustness of these findings, adding confidence that they are not artifacts of variable ordering. This underscores a dual challenge: sustaining fiscal stability while advancing an effective energy transition.

5.2. Implications for Mexico's Energy Policy

The FEVD results show that CO_2 emissions, crude oil production, and public expenditure remain tightly intertwined with oil revenues and prices. This indicates that fiscal stability and environmental outcomes continue to depend on PEMEX's performance. For policymakers, the findings highlight the urgency of diversifying public revenues away from oil rents and fostering an institutional framework that attracts private renewable investment. Without such reforms, the renewable sector will remain indirectly financed by hydrocarbon cycles, limiting its ability to deliver sustained economic returns and emissions reductions.

Granger causality and GIRF results provide further insights. Public expenditure emerges as a non-negligible driver, influencing both oil prices and coal-fired generation, thereby revealing the fiscal–energy transmission channel. The dependence of coal-fired generation on nearly all other variables underscores its dual vulnerability: it absorbs but does not generate systemic impulses, while imposing economic and environmental costs. Transitioning away from coal-based capacity toward renewable sources such as solar photovoltaics, onshore wind, or geothermal—areas where Mexico holds clear comparative advantages—appears essential. Although politically and economically challenging, such a transition aligns with long-term growth and climate commitments. Modernizing PEMEX and strengthening the renewable framework should therefore be seen as complementary rather than competing priorities.

5.3. Limitations and Future Research

This study has several limitations. First, the VAR framework assumes linear and short-run relationships, which may overlook potential nonlinearities or structural breaks in Mexico's energy history. Although generalized IRFs mitigate sensitivity to variable ordering, structural or Bayesian VARs could provide stronger causal inference and a more flexible treatment of uncertainty (Lütkepohl, 2005).

Second, the empirical design deliberately focuses on short- and medium-term dynamics through a reduced-form VAR specification. Future research could extend this framework toward structural and long-run formulations—such as SVAR or VECM models—to evaluate the persistence and equilibrium linkages that underpin Mexico's energy–economy system.

Finally, hybrid econometric–machine learning approaches—such as ARIMA–LSTM or GARCH–LSTM—offer promising avenues for capturing nonlinear and regime-dependent dynamics while enhancing forecasting performance. Future work by the authors will further explore these hybrid frameworks in the context of Mexico's energy and fiscal systems.

6. Conclusions

This study employed a vector autoregression (VAR) framework, complemented with impulse response functions (IRFs), forecast error variance decomposition (FEVD), Granger causality tests, and generalized IRFs (GIRFs), to examine the statistical interrelations of Mexico's energy–economy system. The results confirm that oil rents and PEMEX remain central drivers of GDP growth and fiscal stability, while renewable energy capacity, although expanding, has yet to exert an autonomous impact on economic performance. In addition, the vulnerability of GDP to oil price shocks highlights the urgency of modernizing PEMEX's operations and diversifying revenue sources. Granger causality analysis reinforces these findings by showing that oil prices, oil rents, and GDP are predictive sources of variation, whereas coal-fired generation and emissions function mainly as outcomes, reflecting the asymmetric structure of Mexico's energy system. GIRFs further validate the robustness of these relationships, ensuring that the main conclusions are not artifacts of identification assumptions. Beyond capturing statistical dependencies, the VAR-based framework also functions as a dynamic system model, bridging econometric inference and energy systems simulation.

The policy implications are clear: Mexico requires a dual strategy that enhances PEMEX's efficiency in the short term while establishing institutional and financial mechanisms to accelerate renewable integration. Without such reforms, the renewable sector will remain indirectly dependent on hydrocarbon cycles.

Author Contributions: Conceptualization, J.M. and M.P.; Methodology, J.M., R.M. and M.P; Software, J.M.; Validation, R.M. and M.P.; Formal analysis, J.M. and R.M.; Investigation, J.M. and M.P.; Resources, J.J., D.S., C.G. and J.B.; Data curation, M.P.; Writing—original draft preparation, J.M., R.M. and M.P.; Writing—review and editing, J.M., R.M., J.J., D.S., C.G. and J.B.; Visualization, J.M. and R.M.; Supervision, J.J., D.S., C.G. and J.B.; Project administration, J.J., D.S., C.G. and J.B.; Funding acquisition, J.J., D.S., C.G. and J.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study relies on publicly available datasets obtained from the Banco de México, INEGI, CEFP, World Bank (WDI), SENER/SIE, and PEMEX. Replication code and datasets are openly accessible at https://github.com/Adri0103-coding-mx/Mexico-Energy-Economy-VAR .

Acknowledgments: The authors thank the Instituto Politécnico Nacional (IPN) for academic support, particularly the Escuela Superior de Ingeniería Mecánica y Eléctrica (ESIME), Unidad Zacatenco, as the doctoral program's home institution. We also acknowledge the Centro de Investigación en Computación (CIC) and the Escuela Superior de Economía (ESE) of IPN for their contributions in computational and economic training, respectively. Additional thanks are extended to colleagues from IPICYT for their valuable feedback during this study.

Conflicts of Interest: The authors declare no conflict of interest

Abbreviations

The following abbreviations are used in this manuscript:

VAR	Vector Autoregression
IRF	Impulse Response Function
GIRF	Generalized Impulse Response Function
FEVD	Forecast Error Variance Decomposition
ADF	Augmented Dickey–Fuller (test)
PP	Phillips–Perron (test)
KPSS	Kwiatkowski–Phillips–Schmidt–Shin (test)
AIC	Akaike Information Criterion
BIC	Bayesian Information Criterion
HQIC	Hannan–Quinn Information Criterion
PEMEX	Petróleos Mexicanos
GDP	Gross Domestic Product at current prices
RCAP	Renewable installed capacity (MW)
ORNT	Oil rents (% of GDP)
EMCO	CO_2 emissions (Mt)
KOEP	Energy Use (kg of oil equivalent per capita)
CGEN	Coal-fired gross electricity Generation (GWh)
GEXP	Government Expenditure
OPRD	Crude Oil Production (kb/d)

Appendix A

Full generalized impulse–response chart.

Figure A1. Generalized impulses–responses (GIRF's).

Appendix B

Full impulse–response chart.

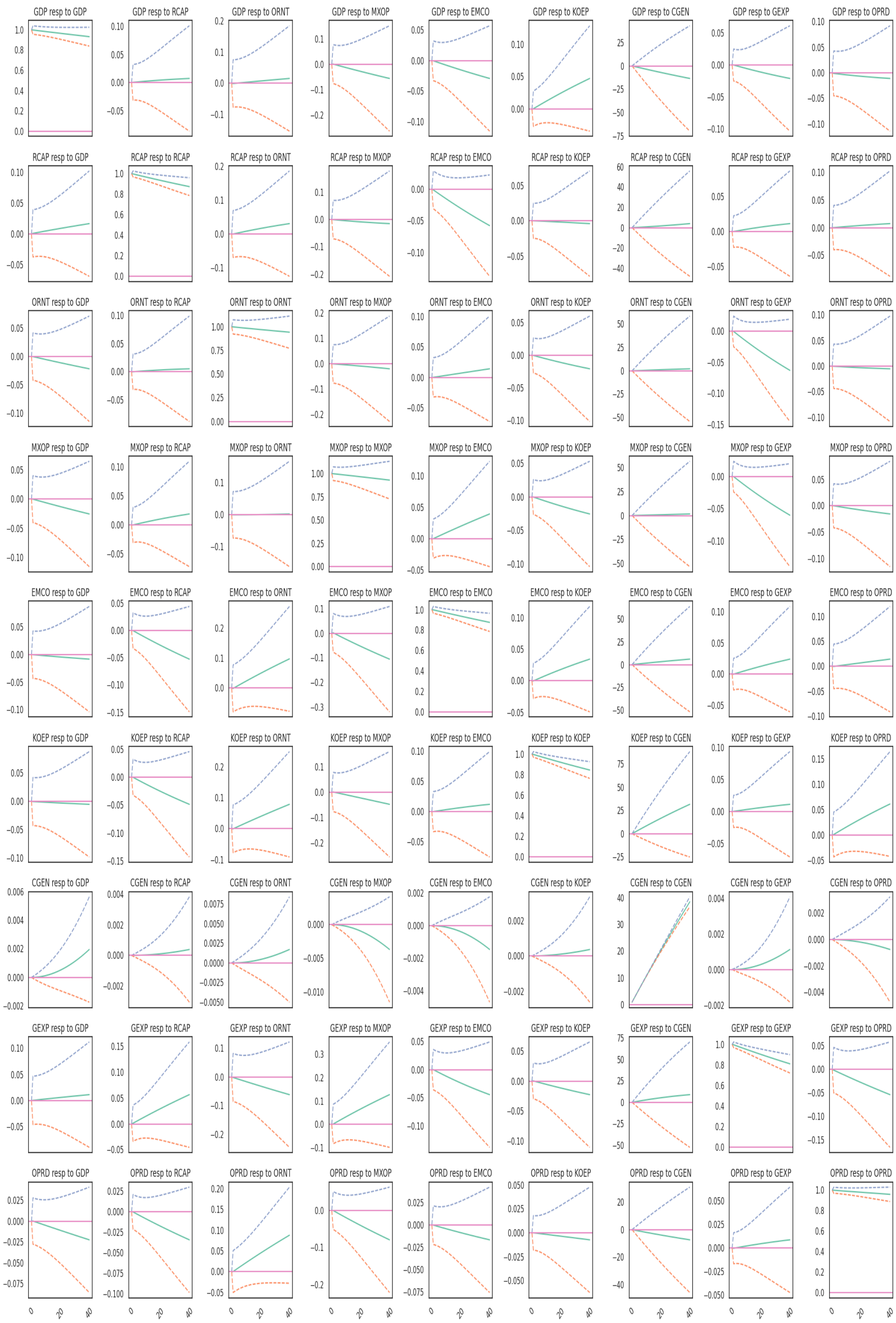

Figure A2. Impulses–responses (IRF's).

Appendix C

Full Forecast Error Variance Decomposition chart.

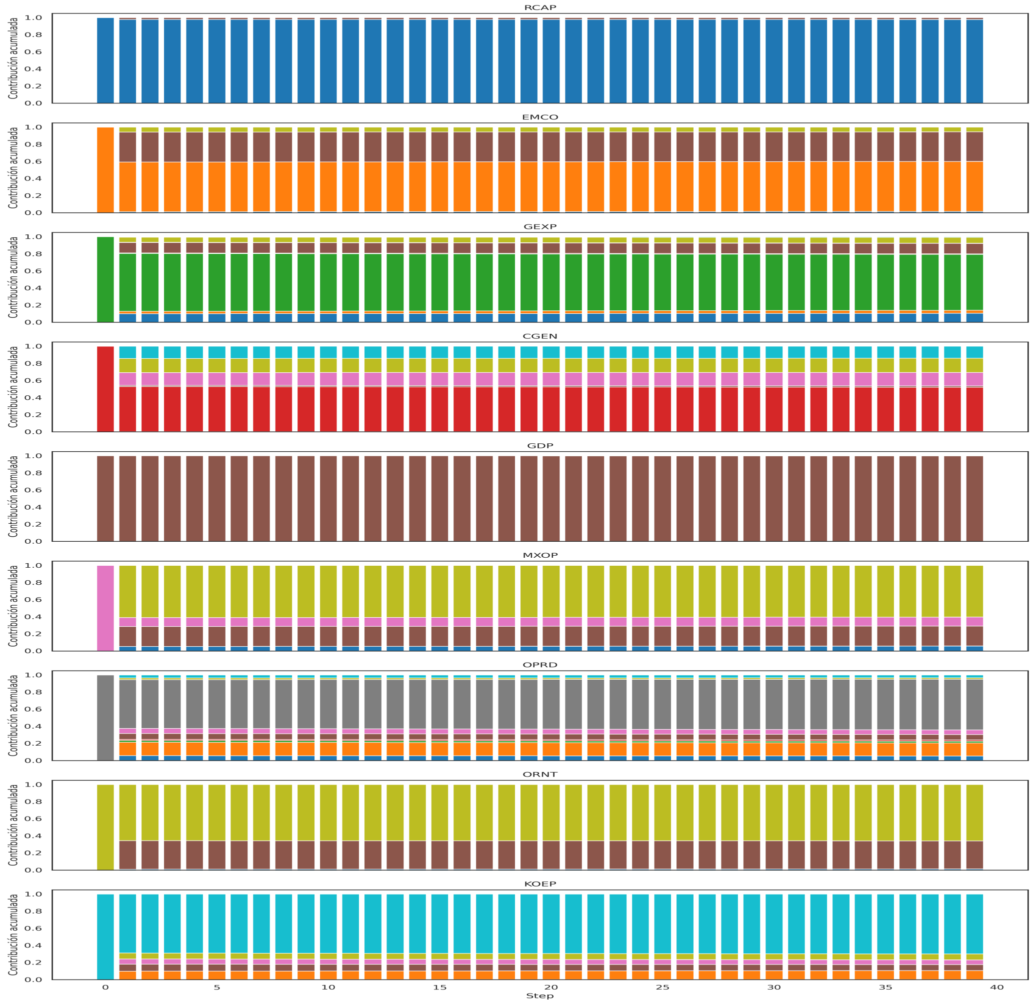

Figure A3. Forecast Error Variance Decomposition (FEVD).

References

Hamilton, J.D. Oil and the macroeconomy since World War II. *J. Polit. Econ.* **1983**, *91*, 228–248. https://doi.org/10.1086/261140.

Sims, C.A. Macroeconomics and reality. *Econometrica* **1980**, *48*, 1–48. https://doi.org/10.2307/1912017.

OECD. *OECD Economic Surveys: Mexico 2024*; OECD Publishing: Paris, 2024. https://doi.org/10.1787/b8d974db-en.

International Monetary Fund (IMF). *Mexico: 2024 Article IV Consultation*; IMF Country Report No. 2024/317, 2024. Available at: https://www.imf.org/en/Publications/CR/Issues/2024/11/01/Mexico-2024-Article-IV-Consultation-and-Review-Under-the-Flexible-Credit-Line-Arrangement-556997.

Natural Resource Governance Institute (NRGI). *Pemex and the Energy Transition: Timely Responses to Growing Threats*; 2025. Available at: https://resourcegovernance.org/publications/pemex-and-energy-transition-timely-responses-growing-threats.

Lütkepohl, H. *New Introduction to Multiple Time Series Analysis*; Springer: Berlin, Germany, 2005. https://doi.org/10.1007/978-3-540-27752-1.

Stock, J.H.; Watson, M.W. Vector autoregressions. *J. Econ. Perspect.* **2001**, *15*, 101–115. https://doi.org/10.1257/jep.15.4.101.

Kousar, S.; Sabir, SA.; Ahmed, F.; Bojnec, Š. Climate Change, Exchange Rate, Twin Deficit, and Energy Inflation: Application of VAR Model. *Energies* **2022**, *15*(20), 7663. https://doi.org/10.3390/en15207663.

Orzechowski, R.; Bombol, M. Energy Security, Sustainable Development and the Green Bond Market. *Energies* **2022**, *15*(17), 6218. https://doi.org/10.3390/en15176218.

Mukhtarov, S.; Yüksel, S.; Mammadov, J. The Impact of Oil Price Shocks on National Income: Evidence from Azerbaijan. *Energies* **2021**, *14*(6), 1695. https://doi.org/10.3390/en14061695.

Koengkan, M.; Fuinhas, J.A.; Marques, A.C. Energy consumption and economic growth nexus in Latin American countries: Evidence from a panel ARDL model. *Energy Reports* **2019**, *5*, 1224–1236. https://doi.org/10.1016/j.egyr.2019.08.004.

Marín-Rodríguez, J.; Pereira, J.; Gómez, F. Economic policy uncertainty and energy shocks in Latin America: A TVP-VAR analysis. *Appl. Econ.* **2025**, in press. (DOI forthcoming).

World Bank. World development indicators (WDI). Available online: https://databank.worldbank.org/source/world-development-indicators (accessed on 24 September 2025).
Secretaría de Energía (SENER). Sistema de Información Energética (SIE). Available online: https://sie.energia.gob.mx (accessed on 24 September 2025).
PEMEX. Anuario estadístico y reportes operativos/financieros. Available online: https://www.pemex.com (accessed on 24 September 2025).
International Energy Agency (IEA). IEA data and statistics. Available online: https://www.iea.org/data-and-statistics (accessed on 24 September 2025).
Instituto Nacional de Estadística y Geografía (INEGI). Banco de información económica. Available online: https://www.inegi.org.mx (accessed on 24 September 2025).
Banco de México (Banxico). Statistics and indicators. Available online: https://www.banxico.org.mx (accessed on 24 September 2025).
Dickey, D.A.; Fuller, W.A. Distribution of the estimators for autoregressive time series with a unit root. *J. Am. Stat. Assoc.* **1979**, *74*, 427–431. https://doi.org/10.1080/01621459.1979.10482531.
Kwiatkowski, D.; Phillips, P.C.B.; Schmidt, P.; Shin, Y. Testing the null hypothesis of stationarity against the alternative of a unit root. *J. Econom.* **1992**, *54*, 159–178. https://doi.org/10.1016/0304-4076(92)90104-Y.
Phillips, P.C.B.; Perron, P. Testing for a unit root in time series regression. *Biometrika* **1988**, *75*, 335–346. https://doi.org/10.1093/biomet/75.2.335.
Engle, R.F.; Granger, C.W.J. Cointegration and error correction: Representation, estimation, and testing. *Econometrica* **1987**, *55*, 251–276. https://doi.org/10.2307/1913236.
Johansen, S. Estimation and hypothesis testing of cointegration vectors in Gaussian vector autoregressive models. *Econometrica* **1991**, *59*, 1551–1580. https://doi.org/10.2307/2938278.
Sims, C.A.; Stock, J.H.; Watson, M.W. Inference in linear time series models with some unit roots. *Econometrica* **1990**, *58*, 113–144. https://doi.org/10.2307/2938337.
Akaike, H. A new look at the statistical model identification. *IEEE Trans. Autom. Control* **1974**, *19*, 716–723. https://doi.org/10.1109/TAC.1974.1100705.
Schwarz, G. Estimating the dimension of a model. *Ann. Stat.* **1978**, *6*, 461–464. https://doi.org/10.1214/aos/1176344136.
Hannan, E.J.; Quinn, B.G. The determination of the order of an autoregression. *J. R. Stat. Soc. Ser. B* **1979**, *41*(2), 190–195. https://doi.org/10.1111/j.2517-6161.1979.tb01072.x.
Blanchard, O.J.; Quah, D. The dynamic effects of aggregate demand and supply disturbances. *Am. Econ. Rev.* **1989**, *79*, 655–673.
Uhlig, H. What are the effects of monetary policy on output? Results from an agnostic identification procedure. *J. Monet. Econ.* **2005**, *52*, 381–419. https://doi.org/10.1016/j.jmoneco.2004.05.007.
Pesaran, M.H.; Shin, Y. Generalized impulse response analysis in linear multivariate models. *Econ. Lett.* **1998**, *58*, 17–29. https://doi.org/10.1016/S0165-1765(97)00214-0.
Koop, G.; Pesaran, M.H.; Potter, S.M. Impulse response analysis in nonlinear multivariate models. *J. Econom.* **1996**, *74*, 119–147. https://doi.org/10.1016/0304-4076(95)01753-4.
Kilian, L.; Lütkepohl, H. *Structural Vector Autoregressive Analysis*; Cambridge University Press: Cambridge, UK, 2017. https://doi.org/10.1017/9781108164818.
Granger, C.W.J. Investigating causal relations by econometric models and cross-spectral methods. *Econometrica* **1969**, *37*, 424–438. https://doi.org/10.2307/1912791.
Kilian, L. Not all oil price shocks are alike: Disentangling demand and supply shocks in the crude oil market. *Am. Econ. Rev.* **2009**, *99*, 1053–1069. https://doi.org/10.1257/aer.99.3.1053.