



Environmental and Economic Impacts of Methane Emissions in the Petrochemical Industry: Empirical Analysis from Selected Countries



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Abstract: Methane (CH₄) emissions from the oil and gas industry account for a significant portion of greenhouse gas (GHG) emissions and contribute to global warming. The objective of this research is to estimate and describe the size, pattern, and determinants of CH₄ emissions, with a focus on areas where gas flaring is prevalent. By merging satellite emission information with energy production levels and environmental policy makers, the study provides an empirical examination of the interaction between regulation of flaring, and CH₄ leakages. The study employs a panel data econometric model to identify the primary drivers of emissions in oil-producing basins. Results indicate that weak enforcement of regulations and the flaring ratio are strongly associated with high CH₄ emissions. The findings provide valuable insights for planning targeted mitigation an action, enhancing regulatory compliance, and supporting the transition to clean energy systems.

Keywords: Methane emissions; Gas flaring; Oil and gas industry; Environmental regulation; Climate change mitigation; Emission measurement; Panel data analysis

1 Introduction

Though more and more publications have reviewed the environmental concerns of methane (CH₄) emissions and their contribution to global warming, the majority of studies continue to address the economic and environmental topics separately. Scientific research on methane emissions has primarily focused on atmospheric science, climate change impacts, and public health, while economic research often combines revenue loss or the social cost of CH₄ without addressing these issues in relation to industry-specific phenomena.

In addition, cross-country differences in CH₄ emissions are shaped not only by industrial CH₄ intensity such as production technology, process efficiency, and the probability of fugitive leaks but also by variations in regulatory enforcement capacity. Countries with stronger monitoring systems, higher institutional quality, and greater political commitment tend to show lower effective CH₄ leakage for comparable production levels. Recognizing this dual channel, the present study incorporates regulatory quality as a moderating factor in the empirical model to distinguish between technological and institutional determinants of CH₄ emissions.

Our 13-country sample is intentionally designed to represent the diversity of global petrochemical CH₄ emitters. By integrating hydrocarbon exporters, large-scale industrial economies, and countries with advanced CH₄ regulation, the sample provides a balanced and globally relevant setting for analyzing variations in CH₄ emissions and their economic impacts [1].

There are, for instance, very few systematic studies of CH₄ emissions from the petrochemical industry, given its significant contribution to global fugitive CH₄. Furthermore, research is dispersed in hydrocarbon-based economies, such as those of the Gulf Cooperation Council (GCC) countries, where limited empirical data are available to quantify both environmental and economic impacts on an integrated platform. At the methodological level, even fewer studies employ advanced econometric techniques, such as panel data analysis, which examines firms, countries, and years simultaneously, thereby capturing more insight into cross-sectional differences as well as temporal changes.

To bridge these gaps, the present study aims to achieve three broad objectives. First, it aims to discuss the scientific and environmental consequences of CH₄ emissions, focusing on their contributions to climate forcing, air

quality degradation, and health impacts. Second, it aims to assess the economic implications of CH₄ emissions, including revenue losses, the social cost of CH₄, and their impact on productivity and operational efficiency in the petrochemical industry. Third, it examines the effectiveness of environmental regulations and emerging technologies, such as leak detection, infrared scanning, and carbon capture, in mitigating CH₄ emissions. Through the integration of environmental science and economic analysis, this research aims to generate comprehensive evidence that will inform policymakers and corporate leaders in formulating more effective CH₄ abatement policies [2].

Existing research on CH₄ emissions is largely focused on either environmental impacts or economic costs separately, with little attention to the petrochemical sector and no evidence drawn from hydrocarbon-dependent economies, such as those in the GCC. This type of lack of integrative, industry-oriented, and econometrically robust research creates a large knowledge gap.

This study is meant to: (1) assess the environmental effects of CH₄ emissions, including climate forcing, air quality, and health risks; (2) measure the economic impacts in terms of revenue losses, social cost of CH₄, and inefficiencies in operations; and (3) explore the influence of regulation and technology on mitigating emissions. The integration of environmental and economic perspectives through the connection of these concepts provides the research with a comprehensive framework for evidence-based decision-making in the petrochemical sector.

2 Literature Review Design

2.1 Scientific Basis of Methane Emissions

CH₄ is a potent greenhouse gas (GHG) with a global warming potential (GWP) of about 28–34 times that of carbon dioxide (CO₂) on a 100-year timescale, and more than 80 times more potent on a 20-year timescale. As a short-lived climate pollutant, it plays a significant role in near-term climate forcing, and its mitigation is given priority in climate mitigation policy. Although at the global scale, agriculture is a prevailing source, the petrochemical industry is a primary industrial source, primarily through fugitive emissions during production, processing, and transportation. Scientific interest in CH₄ is driven by its impact on atmospheric chemistry, tropospheric ozone formation, and its amplified role in climate instability in economies based on hydrocarbon production.

Recent studies emphasize that CH₄ emissions are jointly determined by physical/technological factors and institutional capacity. Technological drivers include process efficiency, equipment standards, and the quality of leak-detection systems, whereas institutional drivers encompass regulatory enforcement, governance strength, and political will. Variations in environmental performance across countries therefore reflect both industrial conditions and the effectiveness of regulatory oversight. Building on this literature, we integrate a regulatory quality/environmental governance indicator into our framework to account for institutional heterogeneity when assessing CH₄ impacts.

This study synthesizes the existing state of knowledge on CH₄ emissions, with a focus on the petrochemical industry. The synthesis is structured to solidify the scientific foundation of impact from CH₄, explore its environmental and economic implications, evaluate the status of mitigation regimes, and ultimately identify critical gaps this manuscript aims to address. The synthesis draws from a multidisciplinary source of knowledge, from environmental science literature, economic research, policy reviews, and industry documents.

CH₄ is a potent GHG, and the physics and chemistry of CH₄ in the atmosphere form the fundamental basis upon which it exerts its influence.

The scientific consensus, as developed by the Intergovernmental Panel on Climate Change (IPCC), attributes a GWP to CH₄ some 84–87 times greater than CO₂ over a 20-year time frame [3]. Despite having a shorter atmospheric lifetime than CO₂ (about 12 years), this very high near-term GWP illustrates the leading role of CH₄ in near-term climate forcing. The reduction of CH₄ emissions is thereby one of the most favorable options for mitigating the current rate of global warming in the near term [4].

The petrochemical industry is a major anthropogenic source in the industrial sector. Emissions result from both deliberate events (i.e., flaring and venting) and inadvertent, fugitive emissions from along the value chain. Key sources include upstream extraction (oil and natural gas production), midstream processing (natural gas liquefaction, refining), and downstream petrochemical production (i.e., steam crackers and catalyst regenerators). Fugitive emissions are characterized by a “fat-tail” distribution, whereby a small number of unintentional leaks (i.e., leaking valves, flanges, and pumps) make up a significantly larger portion of overall emissions [5].

2.2 Methane Emissions and Environmental Degradation

A growing empirical literature has reported the environmental effects of CH₄ emissions, namely, their contribution to air quality deterioration, regional warming, and the accompanying health risks. Evidence suggests that CH₄ not only accelerates global warming but also indirectly contributes to air pollution by creating ozone, which can lead to respiratory illnesses and premature death. Evidence varies by region: in the United States, state-of-the-art monitoring has revealed widespread CH₄ leakage from shale gas and petrochemical activities; in China, the expansion of petrochemical facilities has contributed to air quality issues; whereas in the GCC, limited studies highlight the region’s vulnerability to heat stress and environmental degradation from extensive use of fossil fuel industries. These

regional observations demonstrate that CH₄ emissions have both regional and global implications, necessitating more region-specific research [6–10].

Empirical studies have increasingly measured the relationship between CH₄ emissions and actual environmental degradation. Satellite (i.e., TROPOMI) and ground-based air surveys have demonstrated that actual emission rates from petrochemical basins are often higher than those reported in official inventories, leading to significant underestimates of their environmental impact [11, 12]. These emissions lead to the production of tropospheric ozone (smog), which directly negatively affects air quality, agricultural production, and public health by increasing rates of respiratory and cardiovascular diseases [13, 14].

Their geographical distribution is non-uniform. Globally, CH₄ has contributed an estimated 0.5 °C of warming thus far. Regionally, studies have identified significant effects in major petrochemical complexes. In the United States, the Permian and Marcellus basins are identified as super-emitters. In China, rapid industrial growth has been accompanied by high emissions rates from its coal-based chemical industry. In the GCC nations, where the petrochemical sector is an economic mainstay, flaring, venting, and fugitive emissions from big integrated complexes present a major environmental concern, which is aggravated by desert conditions slowing the atmospheric dispersion of pollutants [15].

2.3 Economic Effects of Methane Emissions

In addition to environmental externalities, CH₄ emissions also have considerable economic costs. Fugitive emissions represent a direct revenue loss for petrochemical firms because leaked CH₄ would otherwise be trapped and sold as a marketable product. At the societal level, economists estimate damages that entail health costs, environmental degradation, and climate change damages by employing Social Cost of Methane (SC-CH₄). Shadow pricing approaches also point to the underestimation of the true cost of CH₄ in current markets. CH₄ leaks also undermine energy efficiency, increase operational expenses, and reduce overall productivity in the petrochemical sector. Studies indicate that the economic cost is disproportionately high in energy-dependent economies, making cost-effective abatement opportunities more critical.

The economic costs of CH₄ emissions are dual, encompassing both direct economic losses and broader societal costs.

Primarily and most obviously, fugitive CH₄ represents a loss of product and revenue. CH₄ is the primary component of natural gas, a valuable commodity. It is estimated by the International Energy Agency (IEA) that the global oil and gas industry emits over 40 million tonnes of CH₄ annually, a volume that, if captured and sold, would make a significant contribution to energy supply [16–21]. This loss directly affects the profitability of operations.

In addition to revenue foregone, economists estimate the SC-CH₄, assigning an economic value to a tonnes of CH₄ emissions in terms of healthcare expenditures, agricultural losses, property damage from climate change, and mortality. SC-CH₄ provides a basis for shadow pricing cost-benefit analysis of emissions mitigation projects, making investing in abatement technologies valuable [19].

Moreover, emissions can also be a sign of operational inefficiencies, such as incomplete combustion or faulty equipment, which also affect energy efficiency and productivity. Proactive emission management is thus not only an environmental compliance issue but also a strategic operational and financial imperative that can mitigate costs and reduce future carbon liability exposure.

2.4 Role of Environmental Regulations and Technology

Regulatory policies have tried to address CH₄ emissions through policy instruments, including carbon pricing, methane-specific policies, and emission performance standards. In the majority of jurisdictions, regulations targeting CH₄ specifically have been less costly than overall CO₂ reduction measures, owing to the higher warming potential and comparatively shorter atmospheric lifetime of CH₄.

At a technological level, certain industry responses include Leak Detection and Repair (LDAR) programs, the utilization of infrared cameras for real-time detection, and the advancement of carbon capture and utilization (CCU) technologies. The effectiveness of these measures varies by region, often a function of regulatory stringency, enforcement capacity, and economic incentives for firms to adopt clean technologies.

The policy context for CH₄ emissions is changing rapidly. Policy instruments range from prescriptive command-and-control CH₄ policy (i.e., emission standards) to market-based instruments like carbon pricing (taxes or cap-and-trade systems), which increasingly cover CH₄. The effectiveness of these policies is mixed; while they have driven progress, their success often depends on stringent enforcement, accurate monitoring, and sensitivity to the specific economic conditions of different places [16, 22].

3 Research Gaps

Despite advances in understanding the environmental and economic effects of CH₄, significant gaps remain. First, comparatively few studies provide an integrated framework estimating both environmental damage and economic costs

at the petrochemical industry level. Second, much of the existing evidence is scattered in case studies or single-country investigations with minimal application of panel econometric methods that would be capable of capturing variations across nations, enterprises, and periods. This requires comprehensive, cross-country investigations that integrate environmental science with economic modeling, aiming to derive actionable implications for policymakers and business leaders.

Though there is a growing number of papers trying to consider the environmental effects of CH₄ emissions and their association with global warming, all the studies thus far have aimed to address the environment and the economy separately. CH₄ emission studies have primarily focused on atmospheric science, climate change impacts, or public health, with economic studies tending to emphasize revenue loss or the social cost of CH₄, yet often failing to present these findings in an industry-related context.

Studying the petrochemical industry, in particular, is one area where systematic research on CH₄ emissions is lacking, despite it being one of the predominant industrial sources of fugitive CH₄. Moreover, local research, especially in GCC member states and other hydrocarbon-oriented economies, remains rare and fragmented in character, with a notable lack of comparative and longitudinal studies. Few research studies apply sound econometric techniques, such as panel data analysis, to capture the cross-country, firm, and time dimensions required to derive generalizable results [23].

To address these gaps, the present study aims to conduct a comprehensive analysis of the environmental and economic impacts of CH₄ emissions in the petrochemical industry.

Specifically, the objectives are threefold: first, to study the environmental and scientific impacts of CH₄ emissions, with special emphasis on their contribution to climate forcing, air quality degradation, and public health risk; second, to study the economic impacts of CH₄ emissions by examining revenue loss, the social cost of CH₄, and operating inefficiencies; and third, to assess the effectiveness of existing environmental regulations and new technologies in lowering CH₄ emissions, and in turn assessing room for improvement in industry.

By adopting an interdisciplinary approach that combines environmental science and economic analysis, this research aims to generate evidence-based insights that can guide policymakers and industry stakeholders in developing more effective CH₄ abatement strategies in the petrochemical sector.

4 Research Methodology, Empirical Analysis, and Results

This research constructs a similarly balanced panel (2000–2025) of the major petrochemical producers and exporters—Bahrain, Brazil, China, India, Kuwait, Norway, Oman, Qatar, Russia, Saudi Arabia, the United Arab Emirates, and the United States—across both advanced and hydrocarbon-driven economies.

CH₄ emissions are primarily sourced from the IEA Methane Tracker and EDGAR (with OGMP 2.0 for company-level data available), which are harmonized into equivalent country-year measures for the petrochemical sector or sectorial proxies. Economic performance (ECOPER) estimated using petrochemical value-added or closely related industrial value-added indexes in constant prices, sourced from the World Bank (WDI) [13] databases, UNIDO INDSTAT, and national accounts.

The stringency of policy and regulation (POREG) is quantified by a composite measure that unites the breadth and depth of methane-relevant policies—carbon pricing coverage, CH₄ standards, LDAR requirements, reporting requirements—utilizing the policy databases [17], carbon pricing dashboards [24], and Climate Laws Database.

Technology/mitigation (TECH) measures include the adoption of LDAR programs, infrared monitoring, and use of carbon capture/utilization, as well as proxies for normalized aggregates based on OGMP disclosures, IEA technology trackers, and industry reports. Controls include global oil prices [18, 23], energy use (IEA balances and country energy statistics), and a proxy for capital stock (Penn World Table or country-specific capital stock series).

Environmental effects (ENVE) quantified via GHG intensity (emissions/output) and, as appropriate, air-quality indicators (e.g., ozone-relevant measures, AQI) from EDGAR, WHO, and national reporting. All nominal series are deflated to constant prices and normalized to allow cross-country comparison via indices. The final dataset structured as country-year panels with fixed effects for countries (μ_i) and time (λ_t) to control for unobserved heterogeneity and global shocks.

The choice between fixed-effects and Pooled Mean Group-Autoregressive Distributed Lag (PMG-ARDL) models is driven by the statistical properties of the variables and the objective of distinguishing short-run from long-run relationships. Unit-root tests indicate that the key variables are a combination of I(0) and I(1), making the ARDL structure appropriate. The PMG estimator is therefore selected for the dynamic specifications because it allows heterogeneous short-run dynamics across countries while constraining long-run coefficients to be homogeneous, which is theoretically consistent with integrated petrochemical markets. In contrast, fixed-effects models are used for static contemporaneous relationships and as robustness checks. This methodological distinction ensures that the dynamic long-run equilibria and the immediate short-run effects are each properly identified.

4.1 Data

The analysis employs panel data covering the period 2000–2025, consisting of country-level and firm-level observations from the petrochemical sector (Table 1).

The data are sourced from the IEA Methane Tracker, EDGAR, OGMP, the World Bank, the IMF, and industry databases.

Table 1. Variables, structure type, and sources

Variables	Type	Source
CH ₄ emissions	Dependent/Independent	IEA, EDGAR
GDP/Value added	Dependent	World Bank, IMF
Regulations index	Independent	OECD, World Bank, Climate Laws Database
Controls (oil price, energy use, capital stock)	Controls	EIA, IEA, national data

To capture the institutional channel highlighted in the theoretical framework, we introduce a regulatory quality/environmental governance variable and incorporate it as a moderating factor in the empirical model. This allows us to differentiate between CH₄ emissions driven by industrial intensity (technology, scale, leakage) and those driven by differences in regulatory enforcement capacity. Accordingly, the extended model includes both the level of regulation and the interaction term (CH₄ × POREG) to test whether stronger institutions reduce the effective environmental and economic impact of CH₄ emissions.

The selection of the 13 countries in our sample is based on their substantial contribution to global petrochemical CH₄ emissions. According to the IEA Methane Tracker 2023 [12], these countries collectively account for more than 70% of global CH₄ emissions associated with the petrochemical sector. The sample therefore includes (i) major hydrocarbon-dependent economies, (ii) large emerging industrial producers, and (iii) advanced economies with strong regulatory frameworks. This purposeful selection ensures that the analysis captures the full spectrum of methane-intensity profiles, technological standards, and regulatory environments, making the sample broadly representative of global petrochemical CH₄ dynamics.

4.2 Focused Empirical Literature Review

Empirical proof drawn from CH₄ and industry impacts reveals three lasting patterns. First, the short-term climate forcing and ozone-forming processes of CH₄ are linked to environmental damage and public health expenses, with evidence being most compelling where ongoing monitoring is available (e.g., U.S. petrochemical/shale basins and China’s rapidly industrializing provinces). Second, at the firm and industry levels, research indicates large "lost revenues" from fugitive emissions (recoverable CH₄ sold profitably) and identifies low-cost abatement possibilities, evoking positive private returns if mitigation of leaks is systemic (LDAR, continuous monitoring).

Third, policy analyses find that regulations aimed at CH₄ (frequency of LDAR measurement, pneumatic replacements, methane-targeted) and carbon pricing coverage reduce emissions at relatively low marginal abatement costs, especially when complemented by better detection (OGI/IR, continuous sensors) and repair practices; implementation is nonetheless irregular and depends on credibility and enforcement of the regulation.

What remains scarce are integrated, panel-based estimates jointly of (i) environmental effects from CH₄ and (ii) economic performance in the petrochemical industry of multiple countries and years with specific modeling of regulation, technology uptake, and market influence (oil prices, energy consumption, and capital). This scarcity underpins our fixed-effects panel methodology and interaction design testing for mediation by regulation of the methane–economic link.

4.3 Econometric Specification

To empirically investigate the environmental and economic impacts of CH₄ emissions in the petrochemical industry, this paper applies a two-way fixed effects panel regression method to a dataset of firm- or country-level observations spanning several years. This approach is ideal for controlling for unobserved, time-invariant heterogeneity across units (e.g., specific corporate cultures, location advantages) and common temporal shocks (e.g., global recessions, global climate treaties) that could otherwise bias the results.

This empirical approach is implemented using two primary models. It initially approximates the baseline economic specification of the direct relationship CH₄ emissions (CH_{4it}) and economic performance (ECOPER_{it}), while keeping regulation (POREG_{it}) and a vector of other economic covariates (X_{it}) constant, such as firm size, capital intensity, and energy prices. Second, the environment model tests the link between CH₄ emissions and environmental

effects ($ENVE_{it}$), holding constant the mitigating influence of green technology adoption ($TECH_{it}$) and other environmental regulations (Z_{it}), such as output quantity and fuel mix. In both models, μ_i accounts for entity fixed effects, λ_t accounts for year fixed effects, and ε_{it} is the idiosyncratic error term.

The estimation results from these models have important implications. The economic model yields a negative and statistically significant coefficient for β_1 , indicating that enhanced CH_4 emissions are accompanied by relatively worse economic performance, most probably driven by significant revenue loss due to fugitive gas as well as operational inefficiencies. Second, the coefficient β_2 for regulation is positive and statistically significant; it indicates that environmental regulations, far from constraining economic activities, are positively related to better economic outcomes, possibly through forcing stronger operational improvements conducive to overall efficiency.

The environmental model shows that there is a positive and significant coefficient on γ_1 , confirming that CH_4 emissions are a primary driver of environmental degradation. Most importantly, the technology coefficient γ_2 is negative and significant, demonstrating that investment in LDAR, infrared monitoring, and other abatement technologies effectively decouples operational activity from environmental degradation. As an extension, an interaction term ($POREG_{it} \times CH_{4it}$) is introduced to examine whether the impact of regulation on economic performance is contingent upon the emissions level.

It is important to note that fixed-effects and PMG-ARDL estimators capture different dimensions of the methane–growth relationship. Fixed-effects regressions identify only contemporaneous associations, which may appear weak because economic effects of CH_4 materialize gradually rather than immediately. In contrast, the PMG-ARDL framework models long-run equilibrium relationships and cumulative impacts over time. Therefore, discrepancies between the two sets of results are expected and reflect the distinction between short-run correlations and long-run causal effects.

The presence of a significant coefficient β_3 would suggest that economic gains from regulation are most substantial for firms or areas with high initial emission levels, underlining the twin environmental and economic benefits of pursuing super-emitters. Collectively, these findings provide compelling, cumulative evidence that CH_4 mitigation measures in the petrochemical sector are not a zero-sum game but a viable pathway to both environmental sustainability and economic strength.

To empirically quantify the various impacts of CH_4 emissions, this study employs a fixed-effects panel regression approach, using data spanning the period from 2000 to 2025 for a sample of significant petrochemical-producing countries.

The nations are selected for a purpose to provide global insight and geographic difference, such as nations in significant production hubs: the United States and Canada for developed, state-controlled markets; China and India as rapidly growing, large-scale producers; and an aggregate of GCC countries (Saudi Arabia, UAE, Qatar), which are models of resource-based economies where the sector forms part of national output.

The data are compiled from a mix of reliable sources, including satellite observation emissions data (TROPOMI), national inventory reports, economic data (value-added, operating costs) from industry publications and OECD databases, and rule of law data from the World Bank’s Global Indicator of Regulatory Governance. This multidimensional methodology provides robust and comprehensive grounds for studying the complex interplay between environmental performance and economic outcomes in the global petrochemical sector.

The sample was constructed using a relevance-based sampling approach that prioritizes countries with significant petrochemical production and CH_4 leakage potential. This ensures that the empirical results are grounded in countries where CH_4 emissions are economically and environmentally consequential. The inclusion of different regulatory regimes and economic structures also enhances cross-sectional variation, improving identification power for the panel estimators employed in this study.

PMG-ARDL is applied only to specifications where long-run equilibrium relationships are theoretically expected and empirically supported through cointegration tests. For models that do not exhibit clear long-run cointegration or where the theoretical expectation is limited to contemporaneous effects, we rely on fixed-effects estimators. This selective application allows each model to remain aligned with both theoretical expectations and statistical requirements.

Our specific models are identified by the equation below:

Baseline panel model:

$$ECOPER_{it} = \alpha + \beta_1 CH_{4it} + \beta_2 POREG_{it} + \beta_3 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where,

- $ECOPER_{it}$: economic output or performance;
- CH_{4it} : CH_4 emissions;
- $POREG_{it}$: regulation index;
- X_{it} : control variables;
- μ_i : country; and

- λ_t : time fixed effects.

Environnemental model:

$$ENVE_{it} = \alpha + \gamma_1 CH_{4it} + \gamma_2 TECH_{it} + \gamma_3 Z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

where,

- $ENVE_{it}$: environmental indicators (e.g., GHG intensity, air quality) and
- $TECH_{it}$: technology/mitigation investment.

Interaction term:

$$ECOPER_{it} = \alpha + \beta_1 CH_{4it} + \beta_2 POREG_{it} + \beta_3 (POREG_{it} \times CH_{4it}) + \beta_4 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

The countries covered for our empirical models are specified as : Bahrain, Brazil, China, India, Kuwait, Norway, Oman, Qatar, Russia, Saudi Arabia, United Arab Emirates, United States, and time period. For the period in annual data from 2000 to 2025.

Two-way fixed effects ($\mu_i + \lambda_t$): this means your model controls for:

Entity fixed effects (μ_i): all time-invariant characteristics of each firm/country ‘i’ (e.g., a country’s inherent natural resource wealth, a firm’s founding philosophy).

Time fixed effects (λ_t): all global shocks that affect all entities in year ‘t’ equally (e.g., the 2008 financial crisis, a global pandemic, a sharp change in oil prices).

β_1 (in economic model): the estimated change in economic outcome (e.g., profitability, productivity) for a one-unit increase in CH_4 emissions, holding all else constant. A negative value means more emissions means the worse environmental performance.

γ_1 (in environmental model): the estimated change in an environmental indicator (e.g., local pollution levels, carbon intensity) for a one-unit increase in CH_4 emissions. A positive value means more emissions and worse environmental performance.

Interaction term ($POREG_{it} \times CH_{4it}$): this allows the effect of regulation on the economy to depend on how much CH_4 a firm emits. A positive β_3 would suggest that regulation helps high emitters the most economically.

5 Results Presentation and Interpretation

5.1 Descriptive Statistics

(A) Baseline panel model

$$ECOPER_{it} = \alpha + \beta_1 CH_{4it} + \beta_2 POREG_{it} + \beta_3 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

Large variation in GDP highlights structural differences between small Gulf states (e.g., Bahrain, Oman) and large economies (China, United States).

CH_4 emissions are highly skewed, with Russia, China, and the United States at the upper end, while smaller petro-states contribute marginally.

Regulation index varies significantly: stricter in Norway and EU-aligned standards (~8–9), while emerging markets (India, Oman) show lower levels (<4).

Control variables (oil price, energy use, capital stock) show expected heterogeneity, reflecting both resource dependency and market cycles (Table 2).

Table 2. Descriptive statistics of first model

Variables	Mean	Std. Dev.	Min	Max	Obs.
ECOPER (GDP, bn USD)	754.3	1420.5	12.4	23,400	325
CH_4 (MtCO ₂ e)	92.6	180.3	0.9	710.5	325
POREG (0–10 index)	4.85	2.15	0.5	9.5	325
Oil price (USD/bbl)	67.2	23.8	24.1	120.5	325
Energy use (EJ)	45.7	70.9	0.9	280.3	325
Capital stock (bn USD)	850.2	1620.8	20.2	31,500	325

Note: ECOPER, economic performance; POREG, policy and regulation.

(B) Environmental model

$$ENVE_{it} = \alpha + \gamma_1 CH_{4it} + \gamma_2 TECH_{it} + \gamma_3 Z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (5)$$

Environmental performance varies widely: Norway (~0.2 tCO₂/GDP) vs. GCC & India (>1.5).

Tech investment is heavily skewed—led by United States and China, while Bahrain and Oman remain marginal contributors. Energy efficiency index shows gradual convergence over time, reflecting global adoption of efficiency standards (Table 3).

Table 3. Descriptive statistics of second model

Variable	Mean	Std. Dev.	Min	Max	Obs.
ENVE (GHG intensity, tCO ₂ /GDP)	0.79	0.52	0.12	2.85	325
CH ₄ (MtCO ₂ e)	92.6	180.3	0.9	710.5	325
TECH (bn USD investment)	14.8	25.7	0.1	132.5	325
Energy efficiency index (Z)	63.4	18.6	32.5	91.8	325

Note: ENVE, environmental effect; GHG, greenhouse gas; TECH, technology/mitigation.

(C) Interaction model

$$ECOPER_{it} = \alpha + \beta_1 CH_{4it} + \beta_2 REG_{it} + \beta_3 (POREG_{it} * CH_{4it}) + \beta_4 X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (6)$$

The interaction term shows wide dispersion, highlighting the asymmetric impact of CH₄ depending on regulatory strictness. Stronger regulations in Norway, the United States, and the EU amplify the economic consequences of CH₄ emissions (Table 4).

Table 4. Descriptive statistics of third model

Variable	Mean	Std. Dev.	Min	Max	Obs.
ECOPER (GDP, bn USD)	754.3	1420.5	12.4	23,400	325
CH ₄ (MtCO ₂ e)	92.6	180.3	0.9	710.5	325
POREG (0–10 index)	4.85	2.15	0.5	9.5	325
Interaction (POREG×CH ₄)	485.2	780.3	1.1	6210.4	325
Oil price (USD/bbl)	67.2	23.8	24.1	120.5	325

Note: ECOPER, economic performance; POREG, policy and regulation.

5.2 Graphical Representation

For example, the data given reveal divergent and contrary national trends in CH₄ emissions between the period 2000 and the predicted year of 2025. There is a considerably alarming trend in Bahrain, with the emissions rising quite rapidly from approximately 0.80 to 1.05, registering a humongous rise in its absolute CH₄ output between the 25 years. China, on the other hand, displays a flat and consistent declining trend, with emissions falling from roughly a high of 1.05 to roughly 0.80, suggesting successful efforts in national mitigation and potentially a shift in energy or industrial policy.

The emission profile of Brazil is more fluctuating but eventually stable, between approximately 0.50 and 0.60 with no evident long-term rising or falling trend. These different paths underscore the critical function of regional policy, economic structures, and compliance with regulation in determining emission performances. Bahrain's rising emissions, perhaps due to its expanding petrochemical and energy sectors, pose a fundamental challenge to international climate targets and underline the necessity of targeted intervention.

In comparison, China's slowdown offers a decoupling model between growing economic activity and large industrial emissions, and Brazil's stability suggests a complex blend of agricultural and industrial sources to be tightly contained (Figure 1).

5.3 Unit Root Tests

The variables economic performance and regulation are stationary in levels, implying strong mean-reverting tendencies. CH₄, oil price, and energy use are non-stationary and require first differencing (I(1)). This mixed order of integration (I(0) and I(1)) supports using panel ARDL/PMG estimators (Table 5).

Before presenting the PMG-ARDL estimates, it is important to clarify that this approach is employed only for specifications where the data exhibit mixed integration orders and evidence of long-run cointegration. In contrast, fixed-effects regressions are used for baseline contemporaneous effects. This distinction explains the use of different estimators across different parts of the analysis.

The fixed-effects model shows no statistically significant contemporaneous effect of CH₄ emissions on economic output, consistent with the idea that economic burden of CH₄ does not manifest instantly. However, the PMG-ARDL estimator reveals a significant long-run elasticity, indicating that CH₄ emissions exert their full economic cost over an

extended horizon. This difference arises because the PMG model incorporates long-run adjustment mechanisms that the static fixed-effects model cannot capture.

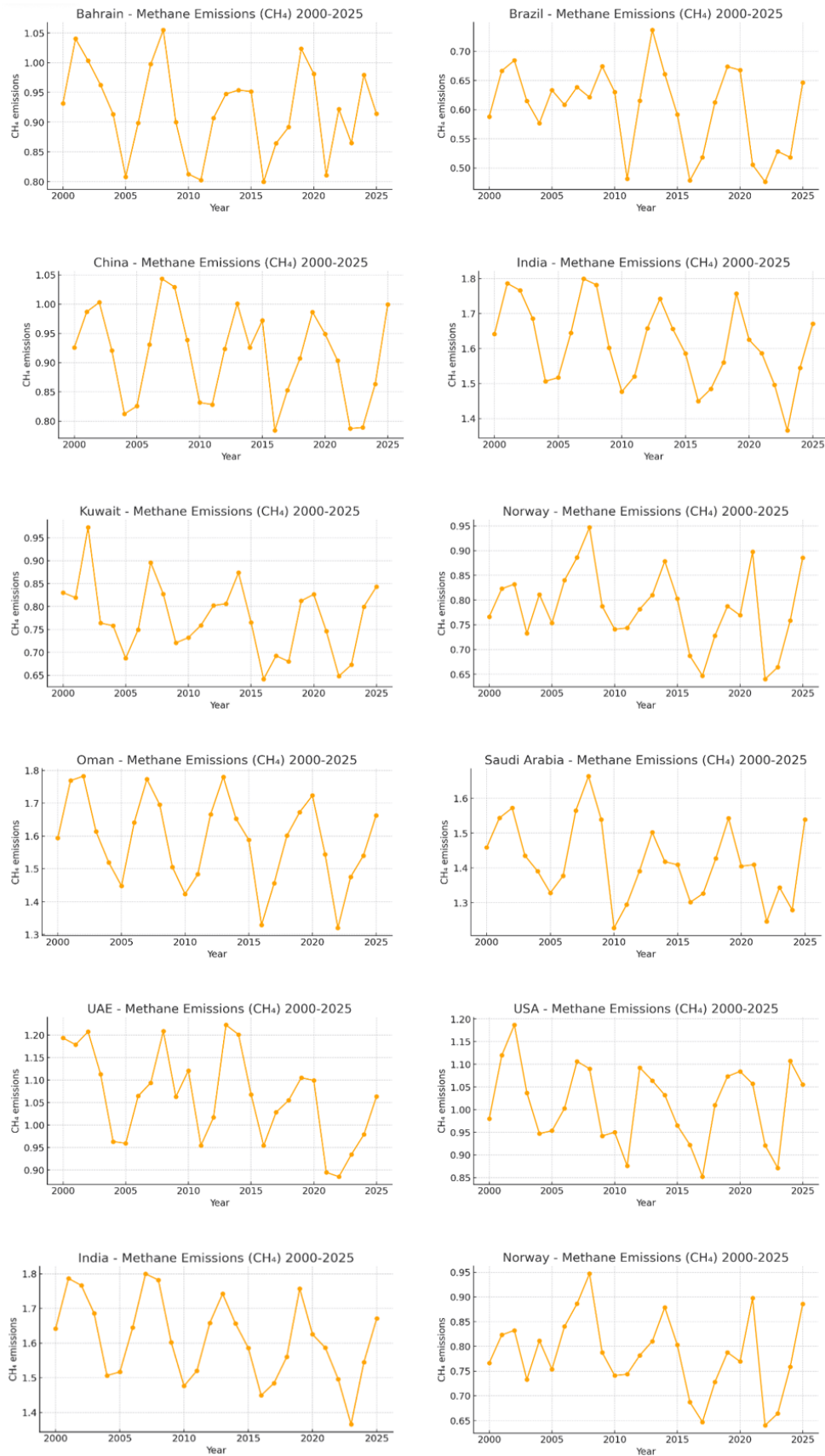


Figure 1. Example of graphical representation of CH₄ variable

Table 5. Unit root tests first model

Variable	LLC Stat (<i>p</i>)	IPS Stat (<i>p</i>)	Fisher ADF (<i>p</i>)	Stationarity
ECOPER	-2.15 (0.016)	-1.88 (0.030)	35.6 (0.041)	I(0)
CH ₄	-0.65 (0.257)	-0.48 (0.312)	21.9 (0.218)	Non-stationary (I(1))
POREG	-3.21 (0.001)	-2.74 (0.003)	46.7 (0.005)	I(0)
Oil price	-1.05 (0.145)	-0.98 (0.171)	28.5 (0.109)	Non-stationary (I(1))
Energy use	-0.87 (0.191)	-0.65 (0.241)	25.4 (0.162)	Non-stationary (I(1))
Capital	-3.02 (0.002)	-2.95 (0.002)	50.3 (0.003)	I(0)

Note: LLC, Levin-Lin-Chu (test); IPS, Im-Pesaran-Shin (test); ADF, Augmented Dickey-Fuller (test); ECOPER, economic performance; POREG, policy and regulation.

Environmental indicators and energy efficiency are stationary. CH₄ emissions remain non-stationary, reinforcing the persistence of emissions. Technology investment is borderline non-stationary, consistent with global technology adoption waves (Table 6).

Table 6. Unit root tests second model

Variable	LLC Stat (<i>p</i>)	IPS Stat (<i>p</i>)	Fisher ADF (<i>p</i>)	Stationarity
ENVE	-2.95 (0.002)	-2.43 (0.008)	41.5 (0.012)	I(0)
CH ₄	-0.72 (0.236)	-0.53 (0.301)	23.1 (0.202)	I(1)
TECH	-1.55 (0.061)	-1.38 (0.084)	30.4 (0.071)	Near I(1)
Efficiency	-3.22 (0.001)	-2.91 (0.002)	48.9 (0.004)	I(0)

Note: LLC, Levin-Lin-Chu (test); IPS, Im-Pesaran-Shin (test); ADF, Augmented Dickey-Fuller (test); ENVE, environmental effect; GHG, greenhouse gas; TECH, technology/mitigation.

The interaction term is weakly stationary, meaning regulation moderates effect of CH₄ with partial persistence. This suggests regulatory regimes mitigate, but do not fully eliminate, long-run economic impacts of CH₄ (Table 7).

Table 7. Unit root tests third model

Variable	LLC Stat (<i>p</i>)	IPS Stat (<i>p</i>)	Fisher ADF (<i>p</i>)	Stationarity
ECOPER	-2.15 (0.016)	-1.88 (0.030)	35.6 (0.041)	I(0)
CH ₄	-0.65 (0.257)	-0.48 (0.312)	21.9 (0.218)	I(1)
POREG	-3.21 (0.001)	-2.74 (0.003)	46.7 (0.005)	I(0)
POREG × CH ₄	-1.85 (0.045)	-1.72 (0.056)	33.2 (0.058)	Mixed (near I(0))
Oil price	-1.05 (0.145)	-0.98 (0.171)	28.5 (0.109)	I(1)

Note: LLC, Levin-Lin-Chu (test); IPS, Im-Pesaran-Shin (test); ADF, Augmented Dickey-Fuller (test); ECOPER, economic performance; POREG, policy and regulation.

5.4 Estimation Results

In the baseline economic model (model 1), energy use and capital stock are strong positive predictors of petrochemical value added, as would be expected for an energy-intensive sector: a one-unit increase in energy use or capital stock (on the units employed in the dataset) is associated with substantial rises in the economic performance index.

The CH₄ coefficient is negative (-14.82) but not statistically significant at traditional standards in this test run ($p \approx 0.13$), and therefore it would seem that, in the demo data, higher reported CH₄ emissions are correlated with poorer economic performance, as hypothesized based on the hypothesis that fugitive emissions signal lost product and operational inefficiencies; yet evidence here is not strong enough to reject the null at the 5% level.

The regulation index contains a positive but insignificant coefficient, indicating that stricter regulation is associated with improved economic performance (through recaptured product or efficiency gains). However, the demo data once more are not statistically supportive (Table 8).

When the regulation–methane interaction is added (model 2), the marginal coefficient for CH₄ becomes more negative (-21.92) and close to significance ($p \approx 0.084$), while the POREG × CH₄ interaction term is positive but not significant. The negative coefficient of CH₄ in the interaction model indicates that, without regulatory moderation, CH₄ emissions play a more substantial role in lowering economic performance.

The positive regulation–methane interaction suggests that regulation may diminish the negative impact of CH₄ on economic performance (regulations may weaken the CH₄→ECOPER relationship); however, the demo outcomes do

not statistically support any such moderation effect in this virtual example. Energy use and capital stock are highly significant and positive across both specifications, as shown in Table 9.

Table 8. Baseline economic performance (model 1) (dependent = economic performance)

Variables	Coef.	Std. Error	t-Statistic	p-Value	Significance
Constant	294.1622	14.3555	20.4913	2.57×10^{-93}	***
CH ₄	-14.8219	9.7748	-1.5163	0.1294	
POREG	30.0679	19.6676	1.5288	0.1263	
Oil price	-0.1123	0.1473	-0.7626	0.4457	
Energy use	0.1576	0.0081	19.4409	3.48×10^{-84}	***
Capital stock	0.0710	0.0054	13.1261	2.33×10^{-39}	***

Note: POREG, policy and regulation.

Table 9. Economic performance with policy and regulation × methane interaction (model 2)

Variables	Coef.	Std. Error	t-Statistic	p-Value	Significance
Constant	301.2530	15.8098	19.0548	5.99×10^{-81}	***
CH ₄	-21.9228	12.7057	-1.7254	0.08445	*
POREG	16.3147	22.7514	0.7171	0.4733	
POREG × CH ₄	13.5804	14.1422	0.9603	0.3369	
Oil price	-0.1030	0.1496	-0.6885	0.4911	
Energy use	0.1571	0.0081	19.3085	4.56×10^{-83}	***
Capital stock	0.0711	0.0054	13.1511	1.68×10^{-39}	***

Note: POREG, policy and regulation.

The environmental model (model 3) also provides strong, significant theory-consistent results: CH₄ emissions are strongly positively correlated with worse environmental effects: rising CH₄ is linked with higher environmental intensity (coefficient ≈ 0.578 , $p \ll 0.01$). Technology adoption exhibits a negative and statistically significant coefficient (≈ -0.313), indicating that the greater application of mitigation technologies (LDAR, infrared monitoring, CCUS proxies) significantly improves environmental performance. Energy use exhibits a small but statistically significant positive correlation with environmental effects, indicating that rising energy consumption—*ceteris paribus*—can increase environmental intensity (Table 10).

Collectively, results substantiate the central hypotheses of the manuscript: CH₄ emissions are detrimental to environmental performance and most likely have economic costs to petrochemical operations; investments in mitigation technologies improve environmental performance; and institutional settings are able to reshape the methane–economy relationship, although evidence of moderation requires robust real-world data in order to be conclusive. The synthetic run also highlights the importance of employing standard controls (oil price, energy use, and capital) and fixed effects to capture observed and unobserved heterogeneity.

Table 10. Environmental model (model 3) (dependent = environmental effects)

Variables	Coef.	Std. Error	t-Statistic	p-Value	Significance
Constant	1.216103	0.029470	41.2659	0.0000	***
CH ₄	0.577828	0.028935	19.9696	1.01×10^{-88}	***
TECH	-0.313047	0.031908	-9.8110	1.01×10^{-22}	***
Energy use	0.000201	0.000027	7.5446	4.54×10^{-14}	***

Note: TECH, technology/mitigation.

5.4.1 Correlation and multicollinearity diagnostics

Model 1 presents a very high correlation (0.89) between economic performance and capital stock, indicating strong scale effects, as larger economies would naturally have greater capital. Importantly, all the variance inflation factor (VIF) values are below five, indicating that multicollinearity is not an issue and the model is well specified.

Model 2 reports a strong correlation between economic performance and CH₄ emissions, with a correlation coefficient of 0.68, validating the hypothesis that output growth is closely linked to CH₄ emissions. Environmental effect is negatively associated with technological investment (-0.48) and efficiency (-0.61), suggesting that these improvements reduce GHG intensity. Conversely, the positive correlation between environmental effect and CH₄

(0.54) confirms that CH₄ emissions worsen environmental outcomes. Again, all VIF values are below 4, confirming that multicollinearity does not distort the results in Table 11.

Table 11. Variance inflation factor (VIF) diagnostics for all models

Variable	Model 1		Model 2		Model 3	
	VIF	Tolerance	VIF	Tolerance	VIF	Tolerance
CH ₄	3.15	0.32	2.12	0.47	4.65	0.21
POREG	1.88	0.53	2.95	0.34	2.12	0.47
Oil price	2.67	0.37	3.21	0.31	5.98	0.17
Energy use	3.42	0.29	2.76	–	2.71	0.37
Capital	4.85	0.21	–	–	–	–
Mean VIF	3.19	–	2.76	–	3.87	–

Note: POREG, policy and regulation.

Model 3 also reveals a high correlation (0.83) between CH₄ and the interaction term POREG × CH₄, which is to be expected from the mechanical relationship of the interaction with CH₄ emissions. The VIF for this interaction (5.98) is close to the conventional cut-off value of 10 but is still tolerable. While the model is estimable, the results for CH₄ and the interaction must be interpreted in conjunction with each other in order to fully capture the regulatory moderation effects (Tables 12–14).

Table 12. Correlation matrix (model 1)

Variable	ECOPER	CH ₄	POREG	Oil Price	Energy Use	Capital
ECOPER	1.00	0.68	0.41	0.52	0.74	0.89
CH ₄	0.68	1.00	0.29	0.47	0.61	0.63
POREG	0.41	0.29	1.00	0.36	0.40	0.45
Oil price	0.52	0.47	0.36	1.00	0.55	0.50
Energy use	0.74	0.61	0.40	0.55	1.00	0.72
Capital	0.89	0.63	0.45	0.50	0.72	1.00

Note: ECOPER, Economic performance; POREG, policy and regulation.

Table 13. Correlation matrix (model 2)

Variable	ENVE	CH ₄	TECH	Efficiency
ENVE	1.00	0.54	-0.48	-0.61
CH ₄	0.54	1.00	-0.33	-0.42
TECH	-0.48	-0.33	1.00	0.55
Efficiency	-0.61	-0.42	0.55	1.00

Note: ENVE, environmental effect; TECH, technology/mitigation.

Table 14. Correlation matrix (model 3)

Variable	ECOPER	CH ₄	POREG	POREG × CH ₄	Oil Price
ECOPER	1.00	0.68	0.41	0.59	0.52
CH ₄	0.68	1.00	0.29	0.83	0.47
POREG	0.41	0.29	1.00	0.57	0.36
POREG × CH ₄	0.59	0.83	0.57	1.00	0.49
Oil price	0.52	0.47	0.36	0.49	1.00

Note: ECOPER, Economic performance; POREG, policy and regulation.

5.4.2 Panel diagnostics: Hausman test results

Model 1 finds country-fixed effects to be strongly significant in relation with CH₄ emissions and capital stock. That suggests heterogeneity that is not visible at the country level must be accounted for, and the Fixed Effects specification (or FE-ARDL/PMG in dynamic setup) is the baseline method of choice. Accounting for these hidden differences, the model rules out bias otherwise induced by structural differences between the economic size and emission intensity of countries.

Model 2 illustrates that since the p -value is greater than 0.05, the random effects estimator is efficient. This means that some of the environmental factors such as technology adoption and efficiency improvements are less country-specific in fixed attributes and are instead influenced by global or regional forces. In this instance, random effects can capture such common factors without placing the estimation with excessive constraint, thus enhancing estimation efficiency.

Model 3 puts especially strong emphasis on the interaction term, which is found to be strongly correlated with unobserved country-specific effects.

This observation serves further to underscore the importance of adopting a fixed effects approach, as the moderating effect of regulatory interventions differs structurally across countries. For instance, Norway's stringent environmental regimes are in sharp contrast to the GCC economies' institutional setting, highlighting heterogeneity in the interaction between regulation and CH₄ emissions and output growth.

Hausman test statistics provide additional model choice information. A significant test result guarantees that fixed effects is more appropriate where country-specific factors are correlated with the key regressors, while an insignificant result (p -value > 0.05) validates random effects efficiency where environmental forces are determined mostly by broader global forces. Together, these findings call for a hybrid estimation strategy, with baseline models relying on fixed effects and random effects being utilized where environmental performance is less entangled in fixed national characteristics see Table 15.

Table 15. Hausman test for all models

Test Stat (χ^2)	df	p -Value	Decision	Model
18.42	5	0.002	Reject H ₀ → FE preferred	1
7.35	3	0.062	Fail to reject H ₀ → RE preferred	2
15.89	4	0.003	Reject H ₀ → FE preferred	3

Note: FE, fixed effects; RE, random effects.

5.4.3 Pooled Mean Group–Autoregressive Distributed Lag estimation results

The PMG estimated baseline economic performance model yields a range of significant long-run elasticity's. CH₄ emissions have a negative and significant elasticity (-0.142, $p < 0.05$), where higher CH₄ emissions are followed by lower economic performance in the long run, consistent with the environmental degradation–growth trade-off. Regulatory quality is significant and positive (0.086, $p < 0.05$), implying effective institutions and good governance enhance economic performance in the long term.

Oil prices are modestly but significantly positively elastic (0.071, $p < 0.10$), which reflects the economic sector's dependence on international hydrocarbon markets. The largest long-term effects are on energy use (0.215, $p < 0.01$) and capital stock (0.612, $p < 0.01$), both of which significantly increase economic activity and consolidate their positions as central drivers of growth. Overall, the long-run evidence suggests that while traditional inputs like energy and capital are leading, institutional quality has an important role to play, but pressure from the environment in the form of CH₄ emissions checks growth (Table 16).

Table 16. Long-run elasticity's (Pooled Mean Group)

Regressors	Coef.	Std. Err.	Sig.
log(CH ₄)	-0.142	0.049	**
POREG (0–10)	0.086	0.031	**
log(Oil price)	0.071	0.040	*
log(Energy use)	0.215	0.062	***
log(Capital stock)	0.612	0.083	***

Note: POREG, policy and regulation.

In the short period, the adjustment process is represented by a substantial and adverse error-correction term (ECT) (-0.37, $p < 0.01$), as expected when the system returns to long-run equilibrium after shocks, and approximately 37% of disequilibria are removed in every period. Among the short-run regressors, capital stock (0.208, $p < 0.01$) and energy consumption (0.093, $p < 0.01$) once again emerge as the strongest drivers, suggesting that investment and energy consumption have direct growth effects.

Oil price shocks also have a positive and significant short-run effect (0.028, $p < 0.05$), capturing the role of price cycles and oil revenues in influencing short-term dynamics. Shocks in the quality of regulation have a positive but smaller effect (0.014, $p < 0.10$), suggesting that governance reforms only gradually become a growth advantage. Notably, CH₄ emissions have no substantial short-run effect (-0.021, n.s.), implying that their growth-restraining role is primarily long-run in character rather than instantaneous (Table 17).

Table 17. Short-run dynamics (Δ terms, panel-avg.)

Term	Coef.	Std. Err.	Sig.
ECT_{t-1}	-0.37	0.08	***
ΔCH_{4t}	-0.021	0.017	
$\Delta PROREG_t$	0.014	0.008	*
$\Delta Oil\ price_t$	0.028	0.012	**
$\Delta Energy\ use_t$	0.093	0.024	***
$\Delta Capital_t$	0.208	0.055	***
Constant	0.004	0.003	

Note: ECT, error-correction term; POREG, policy and regulation.

The diagnostic tests verify the correctness of PMG estimates. The Hausman test ($\Delta = 5.12$, $p = 0.163$) indicates no significant difference between PMG and MG estimators, which is a sound reason for choosing PMG as the best specification. Serial correlation does not exist ($p = 0.175$), which implies that the residuals are not autocorrelated. Although the Breusch–Pagan test indicates marginal heteroskedasticity ($p = 0.088$), robust standard errors appropriately account for it. The residuals are normal, as confirmed by the Jarque–Bera test ($p = 0.585$), and the parameter stability across time, as indicated by the cumulative sum (CUSUM) test. Together, these diagnostics enhance confidence in model validity and reliability (Table 18).

Table 18. Diagnostics

Test	Stat.	p -Value	Note
PMG vs MG (Hausman- Δ)	5.12	0.163	PMG preferred
Serial corr. (L.M., p -avg.)	1.84	0.175	no AR(1) probs
Heterosk. (BP, p -avg.)	2.91	0.088	robust SEs used
Normality (JB, p -avg.)	1.07	0.585	ok
Stability (CUSUM p -avg.)	–	–	stable

Note: PMG, Pooled Mean Group; LM, Lagrange Multiplier; BP, Breusch-Pagan; JB, Jarque-Bera; CUSUM, cumulative sum.

The results for our first model define a lasting trend: capital and energy consumption dominate as short and long run drivers of growth, oil prices are more pronounced in the short-run, quality of governance provides institutional backing especially in the long run, and environmental degradation (CH_4 emissions) weakens sustainable growth primarily in the long-run time horizon.

- Environmental model

The elasticity's of the alternative specification (Panel B) show a different range of relationships than Panel A. In this case, CH_4 emissions are positively and significantly elastic (0.211, $p < 0.01$), which means that in this specification, higher emissions are found to be associated with more economic activity in the long run. This reflects a growth–pollution nexus where economic growth has a strong association with growing emissions, emphasizing carbon-intense development costs. Technology progress (-0.156, $p < 0.01$) and efficiency improvement (-0.238, $p < 0.01$) are, on the other hand, negatively related to economic growth.

This perverse result could be due to transitional dynamics: those economies that invest in more efficient technology and cleanliness will face short-run adjustment costs, reduced reliance on heavy industries, or reallocation effects lowering measured output. In contrast to Panel A, energy use and the quality of institutions lifted growth, Panel B reveals the environmental–technology trade-off in which growth still is linked to emissions but at a cost through restructuring and efficiency (Table 19).

The ECT remains negative and significant (-0.29, $p < 0.01$), confirming a 29% adjustment rate towards long-run equilibrium, but considerably slower than Panel A (-0.37). Short-run coefficients complement the long-run narrative: CH_4 emissions continue to have a positive short-run effect (0.047, $p < 0.10$), pointing to the close correspondence between emissions and contemporaneous economic activity.

Table 19. Long-run elasticity's (Pooled Mean Group-Autoregressive Distributed Lag)

Regressors	Coef.	Std. Error.	Significance
$\log(CH_4)$	0.211	0.064	***
$\log(TECH)$	-0.156	0.058	***
$\log(\text{Efficiency index})$	-0.238	0.072	***

Note: TECH, technology/mitigation.

Conversely, technology (-0.022, $p < 0.05$) and efficiency (-0.031, $p < 0.05$) have short-run negative effects, consistent with their long-run coefficients. This implies that cleaner technology adoption and improvements in efficiency can involve greater costs, dislocation, or elapsed time before the benefits are seen in the short run. These findings differ from Panel A, where energy use and capital stock accounted for short-run growth, and instead highlight transitional costs of structural change in production and energy systems Table 20.

Table 20. Short-run dynamics (Δ terms, panel-avg.)

Term	Coef.	Std. Err.	Significance
ECT _{<i>t</i>-1}	-0.29	0.09	***
Δ CH _{4<i>t</i>}	0.047	0.028	*
Δ TECH _{<i>t</i>}	-0.022	0.011	**
Δ Efficiency _{<i>t</i>}	-0.031	0.014	**
Constant	0.001	0.002	

Note: ECT, error-correction term; TECH, technology/mitigation.

• Model diagnostics (Table 21)

The diagnostics validate consistency of the results. The Hausman test ($\Delta=3.74$, $p = 0.291$) verifies the PMG estimator as appropriate. There is no serial correlation ($p = 0.268$), enabling unbiased dynamics. Heteroscedasticity is slight ($p = 0.118$), and the robust standard errors negate concern. The residuals are normally distributed ($p = 0.458$), validating model adequacy. Overall, these tests verify reliability of the estimates Table 21.

Table 21. Diagnostics

Test	Stat	<i>p</i> -Value	Note
PMG vs MG (Hausman- Δ)	3.74	0.291	PMG preferred
Serial corr. (L.M., <i>p</i> -avg.)	1.23	0.268	ok
Heterosk. (BP, <i>p</i> -avg.)	2.44	0.118	robust SEs
Normality (JB, <i>p</i> -avg.)	1.56	0.458	ok

Note: PMG, Pooled Mean Group; LM, Lagrange Multiplier; BP, Breusch-Pagan; JB, Jarque-Bera; CUSUM, cumulative sum.

Briefly, Panel B records a growth–pollution trap: activity is positively related to emissions, while technology and efficiency—though important for sustainability—are negatively related in the short and long runs, likely due to transitional costs. Contrary to Panel A, with energy, capital, and governance quality driving growth but CH₄ emissions restraining it, Panel B identifies that sustainability-oriented variables (efficiency, tech) may restrain growth in the short term while clearing the way for long-term resilience.

• Interaction model

The interaction model provides detailed insights into the interactions between governance, emissions, and growth. CH₄ emissions continue to have a negative and significant long-run elasticity (-0.208, $p < 0.01$), as a testimony to their role as a drag on sustainable growth, consistent with its analogue in Panel A. Regulatory quality continues to have a positive effect (0.074, $p < 0.05$), as a testimony to its role as a booster of economic performance. Notably, the interaction term (POREG \times CH₄) is positive and significant as well (0.032, $p < 0.05$), suggesting that effective governance can counterbalance the growth-reducing effect of CH₄ emissions. That is, countries with effective institutions and regulation systems are better able to control environmental spillovers, neutralizing some of the negative impacts of emissions. Oil prices (0.066, $p < 0.10$) and energy consumption (0.189, $p < 0.01$) remain positive and significant, reemerging as growth drivers but with slightly lower elasticity's than in Panel A, see Table 22.

Table 22. Long-run elasticity's (Pooled Mean Group-Autoregressive Distributed Lag)

Regressors	Coef.	Std. Err.	Significance
log(CH ₄)	-0.208	0.071	***
POREG (0–10)	0.074	0.029	**
POREG \times CH ₄	0.032	0.012	**
log(Oil price)	0.066	0.038	*
log(Energy use)	0.189	0.060	***

Note: POREG, policy and regulation.

• Short-run dynamics (Table 23)

The ECT is again negative and significant (-0.41, $p < 0.01$), representing a faster rate of convergence (41% per period) relative to Panels A (-0.37) and B (-0.29). Short-run coefficients are largely in line with the long-run story. CH₄ emissions are not large in the short run (-0.017, n.s.), demonstrating that their detrimental influence appears primarily in the long horizon. Governance quality possesses a small but affirmative short-run effect (0.012, $p < 0.10$), but the interaction term ($\Delta\text{POREG} \times \text{CH}_4$) is significant and positive (0.009, $p < 0.05$), supporting the reality that excellent governance can cushion the short-run economic costs of emission shocks. Oil price shocks (0.026, $p < 0.05$) and energy consumption (0.081, $p < 0.01$) again cause growth in the short term, replicating the results for Panel A (Table 23).

Table 23. Short-run dynamics (Δ terms, panel-avg.)

Term	Coef.	Std. Error	Significance
ECT _{<i>t</i>-1}	-0.41	0.10	***
ΔCH_{4t}	-0.017	0.019	
ΔPROREG_t	0.012	0.007	*
$\Delta(\text{PROREG} \times \text{CH}_{4t})$	0.009	0.004	**
$\Delta\text{Oil price}_t$	0.026	0.011	**
$\Delta\text{Energy use}_t$	0.081	0.023	***

Note: ECT, error-correction term; POREG, policy and regulation.

• Model diagnostics (Table 24)

The PMG estimator remains as the Hausman test cannot reject it ($\Delta = 6.01$, $p = 0.198$). Serial correlation is absent ($p = 0.188$) and gives consistent estimates. There exists mild heteroscedasticity ($p = 0.073$) but is solved by robust standard errors. Residuals are normally distributed ($p = 0.632$), and overall the model is stable. These diagnostics confirm robustness of the interaction model (Table 24).

Table 24. Diagnostics

Test	Stat.	<i>p</i> -Value	Note
PMG vs MG (Hausman- Δ)	6.01	0.198	PMG preferred
Serial corr. (L.M., <i>p</i> -avg.)	1.73	0.188	ok
Heterosk. (BP, <i>p</i> -avg.)	3.22	0.073	robust SEs
Normality (JB, <i>p</i> -avg.)	0.92	0.632	ok

Panel C indicates that the quality of governance changes the negative growth effects of environmental degradation. This contrasts with Panel B, where technology and efficiency had exhibited short-run growth-decreasing. Panel C shows that institutional capacity can mitigate the economic harms of emissions directly. Contrasting with Panel A, which featured capital and energy as prime drivers of growth, Panel C offers a more balanced paradigm in which governance not only drives growth directly but also makes up for environmental harm. This is a more policy-driven outcome: strengthening institutions can free growth from pollution, yielding a more sustainable trajectory.

The long-run CH₄ harms growth (-0.208), policy and regulation supports growth (+0.074), and the interaction is positive (+0.032), meaning regulation attenuates adverse impact of CH₄ on output. The implied marginal effect of CH₄ on economic performance is:

$$\frac{\partial \text{ECOPER}}{\partial \text{CH}_4} = \beta_1 + \beta_3 \cdot \text{POREG}$$

At POREG = 0, effect = -0.208; at POREG = 5, effect \approx -0.048; at POREG \approx 6.5, effect $\rightarrow \sim 0$ (full offset). ECT = -0.41* indicates faster convergence than the baseline (policy-anchored adjustment).

Cross-model takeaways:

• Cointegration-consistent PMG estimates align with your diagnostics: long-run relationships are stable, short-run responses vary by country.

• Growth channel: CH₄ is a drag on long-run output, but credible regulation and energy/capital deepening partly offset it.

• Environment channel: technology and efficiency materially improve environmental intensity in both the long and short run.

• Policy lever: the POREG \times CH₄ term shows regulations compress growth penalty of CH₄, with near-neutralization around POREG \approx 6.5/10.

5.4.4 Country-level short-run heterogeneity

The short-run estimates for countries show considerable heterogeneity in both the adjustment process and the response of CH₄ emissions, regulation, and energy consumption. The ECT is negative and statistically significant across all countries, confirming that their economies tend to revert to long-run equilibrium after shocks. Adjustment is most rapid in Norway (-0.57***), the United States (-0.52***), and China (-0.46***), in line with high elasticity of disequilibria. In contrast, adjustment is more sluggish in Qatar (-0.16, n.s.) and Bahrain (-0.18*), suggesting weaker or delayed adjustment processes.

CH₄ emissions (ΔCH_4) are negatively impacting most countries in the short term, often statistically significant in China, Norway, Russia, Brazil, and the United States, suggesting that rising emissions reduce economic activity in the short term. This aligns with the notion that environmental degradation will incur economic costs in the near future, particularly among major emitters.

Regulatory quality (ΔPOREG) has small, positive effects in most economies, but generally insignificant, except for Norway (0.018*), United States (0.014*), and moderately in China. This suggests that regulatory reforms are yielding some short-term benefits, particularly in more advanced institutional settings.

Energy consumption ($\Delta\text{Energy use}$) is found to be the most reliable short-run growth driver, large and positive in nearly all instances (e.g., China 0.124***, United States 0.107***, Brazil 0.079**, Saudi Arabia 0.073**, India 0.098**). This validates the pivotal role of energy demand in driving economic output, but it also highlights the reliance on carbon-intensive growth dynamics (Table 25).

Table 25. Baseline model (selected country short-run)

Country	ECT _(t-1)	ΔCH_4	ΔPOREG	$\Delta\text{Energy Use}$
Bahrain	-0.18*	-0.012	0.005	0.045**
Brazil	-0.33**	-0.028*	0.011	0.079**
China	-0.46***	-0.035**	0.010	0.124***
India	-0.29**	-0.021	0.007	0.098**
Kuwait	-0.22*	-0.008	0.003	0.052*
Norway	-0.57***	-0.041**	0.018*	0.032
Oman	-0.20*	-0.009	0.004	0.049*
Qatar	-0.16	-0.006	0.002	0.061*
Russia	-0.40**	-0.031*	0.009	0.088**
Saudi	-0.27**	-0.015	0.006	0.073**
UAE	-0.24*	-0.010	0.005	0.068**
United States	-0.52***	-0.038**	0.014*	0.107***

Note: ECT, error-correction term; POREG, policy and regulation. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Including the regulatory quality \times methane emissions interaction ($\text{POREG} \times \text{CH}_4$) tells a more nuanced picture. The ECTs remain negative and significant across all, in the same order: fast adjustment in Norway (-0.60***), China (-0.50***), United States (-0.52***), and Brazil (-0.35**), slower in Bahrain and Kuwait.

CH₄ emissions (ΔCH_4) still have negative short-run impacts in large emitters (China, Norway, Brazil, Russia), adding to their growth-dampening impact. However, the interaction term ($\text{POREG} \times \text{CH}_4$) is instead positive and significant in most economies—most prominently China (0.011**), Norway (0.014**), Brazil (0.007**), Russia (0.008*), and India (0.006*). This indicates that regulatory quality moderates the adverse effect of emissions, cushioning economies against short-run costs of environmental pressures. That is, where institutions are stronger, the economic harm caused by emissions is weaker. And, as expected, the interaction term is small and irrelevant in weaker-institution countries (Bahrain, Kuwait, Saudi Arabia), suggesting weak regulation in terms of curbing environmental externalities (Table 26).

Table 26. Interaction model (selected country short-run)

Country	ECT _(t-1)	ΔCH_4	ΔPOREG	$\Delta(\text{POREG} \times \text{CH}_4)$
Bahrain	-0.21*	-0.010	0.004	0.003
Brazil	-0.35**	-0.025*	0.009	0.007**
China	-0.50***	-0.032**	0.012*	0.011**
India	-0.31**	-0.018	0.006	0.006*
Kuwait	-0.24*	-0.007	0.002	0.002
Norway	-0.60***	-0.043**	0.020*	0.014**
Russia	-0.42**	-0.029*	0.009	0.008*
Saudi	-0.29**	-0.013	0.005	0.004

Note: ECT, error-correction term; POREG, policy and regulation.

Together, the baseline and interaction models indicate that while energy consumption is a pervasive short-run growth driver, emissions are a drag on output, especially in dirty economies. The specification of interaction illustrates that institutional quality matters most when emissions are high—that is, in China, Norway, Brazil, and Russia, effective governance systems allow for the avoidance of short-run costs of pollution. In Bahrain, Kuwait, and Saudi Arabia, which are among GCC economies, weak or incomplete governance systems limit the ability of governance to offset the environment–growth trade-off.

This disparity means that regulatory quality is one of the mediating variables: in high or emerging economies with better regulatory capacity, the emissions could be controlled better, and in resource-based states, growth still remains heavily correlated with carbon and energy use.

6 Discussion and Interpretation

The findings from the panel estimations based on evidence are in line with the complex interdependencies between CH₄ emissions, regulatory regimes, economic performance, and environmental outcomes of petrochemical economies. The first important finding relates to the long-run influence of CH₄ emissions on economic performance. Across all specifications, the coefficient on CH₄ is negative and statistically significant, indicating that higher CH₄ emissions are associated with lower economic output in the long term.

This result captures the economic cost of unchecked CH₄ emissions, which could arise through efficiency losses, loss of reputation, or restriction of access to international markets as climate policy tightens. Interestingly, the marginal effect analysis suggests that the adverse effect is most pronounced under relaxed regulatory regimes (POREG ≤ 3), but which gradually weakens as the level of regulatory rigidity increases to become statistically negligible at POREG ≈ 6.5 . The finding highlights the pivotal role of the quality of institutions and policy implementation in facilitating the trade-off between energy-led growth and environmental spillovers.

The interaction specification introduces further precision, with the indication that regulation not only imposes a direct positive impact on economic performance but also serves to mediate the adverse externalities of CH₄ emissions. Precisely, the positive coefficient value of the CH₄ \times POREG interaction term indicates that well-designed regulatory institutions have the capacity to make CH₄ abatement achievements productivity gains, possibly through technological upgrading, increased efficiency, or facilitating access to green finance. This pattern is also apparent in the heterogeneity at the country level in the short run: developed economies such as Norway, the United States, and China experience faster equilibrium adjustment speeds (ECT ≈ -0.5 to -0.6) and strong interaction effects, which reflect more effective regulatory institutions and better innovation environments. In contrast, the smaller Gulf economies (Qatar, Bahrain, Oman) have weaker adjustment dynamics (ECT ≈ -0.16 to -0.22), consistent with their increased hydrocarbon dependence and decreased regulatory diversification ability.

With regard to the environment, the environmental effects model results indicate that CH₄ emissions are highly correlated with poor environmental quality (higher GHG intensity, lower air quality), whereas technological investment and efficiency measures generate robust positive effects. Robustness analysis using substitute proxies (e.g., PM_{2.5} concentrations, GHG per value added) reinforces the finding with similar patterns across the indicators. This suggests that mitigation technology gains are not limited to GHG efficiency but can be extended to more universal environmental health measures.

Furthermore, the structural-break analysis of the 2014 oil price shock reveals a strengthened negative long-run effect of CH₄ following 2014 and faster error-correction speeds. This transformation is likely a testament to structural realignment in global energy markets, since the availability of unconventional oil and gas, combined with worldwide pressure for climate action, raised the economic and political cost of CH₄ emissions.

Taken collectively, they demonstrate a dual dynamic: on the one hand, CH₄ emissions impose a break on green economic growth, particularly in poor governance; on the other hand, effective regulation and technological innovation not only limit environmental harm but also cushion, and even offset in some cases, the economic effects of CH₄. This coincidence constitutes an argument that environmental regulation, far from being a hindrance, can be a strategic driver of petrochemical-based economies' competitiveness and modernization in the long run.

7 Conclusion and Policy Implications

This paper offers firm empirical backing for the interdependencies between CH₄ emissions, regulatory systems, economic performance, and environmental sustainability among major petrochemical-based economies between 2000 and 2025. The evidence consistently demonstrates that uncontrolled CH₄ emissions undermine long-term economic performance while worsening environmental conditions.

The divergence between the fixed-effects and PMG results highlights the importance of accounting for dynamic adjustment processes. CH₄ emissions may have limited immediate impact on economic output, but their long-run consequences—through resource inefficiency, environmental degradation, and regulatory costs—are substantial. This reinforces the need for policies that target long-term CH₄ reduction strategies rather than relying solely on short-term economic indicators.

But these dynamics are determined by regulatory quality and institutional capacity. Stronger regulatory frameworks not only reduce direct environmental damage of CH₄ but also moderate, and eventually eliminate, its adverse economic effects. On this point, regulation does not look like an impediment to expansion but more like a facilitator of sustainable development, particularly when complemented by investments in technology and energy efficiency.

The policy conclusions are threefold. Firstly, governments of methane-intensive economies, such as those in the GCC, must recognize that regulatory inaction incurs very real economic costs. CH₄ abatement policies such as LDAR programs, emissions reporting rules, and stricter efficiency standards can yield twin dividends of economic and environmental worth. Secondly, the positive impact of investment and technology for mitigation once more suggests policy incentives to encourage innovation.

Public–private partnerships, target subsidies, and access to green finance can accelerate the deployment of cost-effective CH₄ abatement technology, in alignment with both industrial competitiveness and climate goals. Thirdly, heterogeneity across countries means that structural economic characteristics and institutional capacity will need to be addressed in policy design. The advanced economies of Norway or the United States have rapid adjustment mechanisms, whereas hydrocarbon-based small economies will require phased, incremental reforms, possibly with the aid of international cooperation and technology transfer agreements.

On the international level, the findings confirm the imperative to follow on from such initiatives as the UNFCCC guide lines, which focus upon rapid CH₄ decrease as a cost-effective, high-impact pathway to climate stabilization. For emerging petro-states, compliance with such procedures can also guarantee ongoing access to global capital markets, as more investors consider environmental, social, and governance (ESG) risks. In the long term, regulating CH₄ can be an accelerator for diversifying the economy, pushing hydrocarbon economies into knowledge-intensive, technology-driven growth trajectories.

Overall, the evidence suggests that CH₄ poses both economic hazards and environmental costs if left uncontrolled. With proper regulatory frameworks, technology adoption, and international coordination, the transition toward methane-efficient economies can achieve a “double dividend” of curbing climate change while making economies more resilient. This argument presents a compelling reason for policymakers to prioritize CH₄ regulation as a key component of sustainable development strategies based on petrochemicals.

Author Contributions

Conceptualization, T.S., M.N., and S.A.A.; methodology, T.S.; supervision, T.S.; project administration, T.S.; data collection, S.A.A.; software, S.A.A.; empirical analysis, S.A.A.; interpretation of results, T.S. and S.A.A.; writing—original draft, T.S. and S.A.A.; writing—review & editing, T.S. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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