LEX LOCALIS-JOURNAL OF LOCAL SELF-GOVERNMENT

ISSN: 1581-5374 E-ISSN: 1855-363X
VOL. 23 , NO. 10(2025)

The Effect of the Expansion of U.S. Liquefied Natural Gas Exports and Its Diverse Substitution Patterns on Global Greenhouse Gas Emissions and Environmental Quality: A Panel Data Analysis Using the ARDL Model Covering the Period 1990–2022

Benazza Hicham [1]
Professor of Lecturer B
ORCID: https://orcid.org/0009-0001-0135-7189
Laboratory of Research on Public Governance and Social Economy, ***University Centre Salhi Ahmed – Naama***. (**Algeria**).
benazza.hicham@cuniv-naama.dz
Cadi Mohammed [2]
University Centre Salhi Ahmed –Naama. (**Algeria**)
cadi.mohammed@cuniv-naama.dz
Boumedini Mohamed Amine [3]
Ph.D .Management of Enterprises and Social Capital of the laboratory
MECAS at the Faculty of Economics and Management of the University of Tlemcen
Mohamedamine.boumedini@univ-tlemcen.dz

Received: 01/04/2025 ***Accepted: 10/08/2025*** ***Published: 30/10/2025***

Abstract:
This study investigates the evolution of U.S. liquefied natural gas (LNG) exports and evaluates their impact on global energy market dynamics—particularly in terms of prices, energy security, and environmental quality—over the period 1990–2022. The research employs an econometric framework incorporating LNG exports (X), domestic natural gas production (PL gaz), and GDP growth rate as independent variables, while carbon dioxide emissions (CO_2 E) serve as the dependent variable representing environmental quality. The analysis applies the Autoregressive Distributed Lag (ARDL) bounds testing approach and cointegration techniques to explore the short- and long-run dynamics among the variables.
The empirical findings indicate that U.S. LNG exports have experienced substantial growth over the last decade, reaching approximately 88.3 million tons in 2024, with projections suggesting further expansion to around 16.4 billion cubic feet per day by 2026. This upward trend has been driven by technological advancements, large-scale infrastructure investments, and growing global demand, particularly from European and Asian markets. Nevertheless, this expansion has also introduced environmental challenges and regulatory pressures, underscoring the urgent need for balanced policies that promote sectoral sustainability while mitigating adverse climate impacts.
The econometric results further demonstrate that, in the long run, the expansion of LNG exports has a significant and positive effect on carbon dioxide emissions in the United States. Additionally, per capita GDP growth emerges as a key factor contributing to higher carbon emissions, alongside a strong positive long-term association between CO_2 emissions and domestic natural gas production. These results highlight the necessity of integrating environmental sustainability into future strategies for the continued development of the U.S. LNG export sector.

Keywords: U.S. liquefied natural gas exports; domestic natural gas production; carbon emissions; environmental quality; ARDL; GDP growth rate.
JEL Classification: Q58; Q43; C32

1-Introduction:

The pace of emissions reduction in the United States is currently insufficient to meet the target set by the Paris Agreement for 2030, which calls for a 50–52% reduction in emissions compared to 2005 levels, or the more recent 2035 target aiming for a 61–66% reduction (Al-Mulali & Oztur, 2015). To achieve the 2030 goal, U.S. emissions would need to decline at an average annual rate of 7.6% between 2025 and 2030 (Prest & Forthcoming, 2024). For comparison, emissions in 2020 fell by 11% due to the strict mobility and economic restrictions imposed during the COVID-19 pandemic—an exceptional and unsustainable circumstance for the future (Sherwin, Rutherford, Zhang, Che, & al., 2024).

The liquefied natural gas (LNG) sector has experienced substantial growth over recent decades, becoming a cornerstone of the global energy market due to its critical role in enabling gas transportation over long distances where pipeline infrastructure is insufficient. In this regard, the United States has transformed from a net importer into one of the world's leading exporters of LNG. This transition has been driven by innovative strategies to harness domestic energy resources—particularly shale gas—combined with the development of advanced export facilities and infrastructure (Alvarez, Zavala-Araiza, & Lyon, 2018).

This transformation is primarily underpinned by the expansion of natural gas production, which has reached record levels owing to advanced technologies such as hydraulic fracturing. These technological advancements have allowed the United States to elevate LNG exports to unprecedented heights. In 2024, U.S. LNG exports totaled approximately 88.3 million tons, marking a 4.5% increase compared to the previous year. Europe accounted for 55% of total exports, followed by Asia with 34%. Projections suggest that this upward trajectory will continue, with U.S. LNG exports expected to reach 14.2 billion cubic feet per day in 2025—an estimated 19% increase—and further rise to 16.4 billion cubic feet per day by 2026 (DOE, 2024).

The expansion of liquefied natural gas (LNG) exports represents a clear manifestation of the geopolitical and economic transformations reshaping the global energy landscape, particularly in light of the accelerating global pursuit of cleaner and more sustainable energy sources. This upward trend underscores the growing role of the United States in meeting international energy needs, thereby solidifying its standing as a major economic and energy power while enhancing global energy security (Raihan, 2023).

In December 2024, the U.S. Department of Energy released a comprehensive report entitled *"Energy, Economic, and Environmental Assessment of U.S. LNG Exports,"* which examines the effects of continued growth in U.S. LNG exports through 2050. The report evaluates how such expansion influences domestic natural gas prices, global greenhouse gas emissions, and broader economic and social outcomes, drawing comparative insights from an S&P Global analysis (Yergin, 2024).

Within this analytical framework, four primary dimensions are emphasized: methane leakage throughout the gas supply chain, which poses a significant environmental challenge; the domestic price implications of export expansion; the uncertain and volatile global demand outlook for U.S. LNG; and evolving consumer behavior concerning the shift between LNG and alternative energy sources—factors that are pivotal to understanding future transformations in the international energy market (Howarth, 2024).

1-1-Study Problem :

The central research problem concerns the examination of the intricate and dynamic relationship between the expansion of U.S. liquefied natural gas (LNG) exports and their multidimensional impacts on environmental quality, energy prices, and energy security during the period 1990–2022. At its core, the study addresses the extent to which the United States can achieve a strategic balance between promoting economic growth driven by rising LNG exports and fulfilling its commitments to mitigate adverse environmental consequences, particularly carbon dioxide emissions.

The investigation is guided by several fundamental research questions:

- ✓ What is the magnitude of the impact of LNG export expansion on carbon emission levels in the United States?
- ✓ How does such expansion affect local and global environmental quality?
- ✓ Is it feasible for the United States to sustain its leadership in the global LNG market while complying with stringent environmental and climate regulations?
- ✓ What role do domestic natural gas production, transportation, and economic growth play in shaping the causal nexus between LNG exports and environmental quality?

This research problem embodies a multidimensional challenge that integrates economic, environmental, and political considerations. It assesses the potential convergence—or divergence—between national trade strategies and the imperatives of sustainable development in the context of mounting international obligations to achieve emission reduction targets and ensure energy security.

Accordingly, the core objective of the study is to measure the effects of LNG exports (X), domestic natural gas production (PL gaz), and GDP growth rate on environmental quality in Algeria, employing the ARDL modeling framework for the period 1990–2022.

1–2–Study assomptions:

The hypotheses of this study are built upon an examination of the interdependent relationship between the expansion of U.S. liquefied natural gas (LNG) exports and their implications for environmental quality, economic growth, and energy security. They can be articulated as follows:

- ✓ The study posits a long-term positive relationship between the expansion of U.S. LNG exports and the increase in carbon dioxide emissions, thereby exerting a negative impact on environmental quality.
- ✓ It further posits that domestic natural gas production is positively correlated with higher levels of carbon dioxide emissions.
- ✓ The study also hypothesizes that GDP growth stimulates greater energy demand, which consequently contributes to an increase in greenhouse gas emissions.

By empirically testing these hypotheses, the research seeks to provide an objective evaluation of the effectiveness of current policies and to propose evidence-based recommendations that foster sustainable development while achieving a balance between economic progress and environmental preservation.

1-3- Research Objective:

This study aims to investigate and critically analyze the ongoing expansion of U.S. liquefied natural gas (LNG) exports between 1990 and 2022, evaluating its implications for global energy market equilibrium with a focus on three key dimensions: energy prices, energy security, and environmental quality. Employing the Autoregressive Distributed Lag (ARDL) bounds testing methodology, the research develops an econometric framework to explore the dynamic interrelationships among LNG exports, domestic natural gas production, economic growth, and carbon dioxide emissions. The objective is to generate a comprehensive understanding of the economic and environmental consequences arising from this trend and to propose evidence-based policy recommendations that foster sustainable development by striking a balance between economic advancement and environmental protection.

1-4- Study Methodology:

The methodology of this study employs a quantitative analytical approach to assess the impact of the expansion of U.S. liquefied natural gas (LNG) exports on environmental quality and energy markets over the period 1990–2022. An econometric model is developed using the Autoregressive Distributed Lag (ARDL) bounds testing framework, wherein LNG exports, domestic natural gas production, and GDP growth rate are treated as independent variables, while carbon dioxide emissions serve as the dependent variable and the principal indicator of environmental quality. The analysis utilizes data sourced from the World Bank database.

This methodological approach provides a robust and systematic framework for examining the intricate interrelationships between economic and environmental variables. It enhances the capacity to derive evidence-based insights and develop practical recommendations that can guide effective policymaking toward achieving sustainable development goals.

1-5- Study Plan:

This study is structured into two principal sections, followed by the presentation of results and recommendations:

- ✓ The theoretical framework accompanied by a review of significant prior economic research.
- ✓ An empirical assessment of the impact of expanding U.S. liquefied natural gas (LNG) exports on environmental quality.

2. Theoretical Framework and Review of Key Economic Literature

The theoretical framework of this study establishes the conceptual basis for analyzing the relationship between the expansion of liquefied natural gas (LNG) exports and their implications for environmental quality and global energy markets. Rooted in the principles of environmental economics, the study emphasizes the interactive relationship between economic growth and natural resource consumption, as well as the resulting effects on greenhouse gas emissions and environmental quality (Akhbari & Nejati, 2019).

Fundamental economic theories advocate for a balance between sustainable economic development and environmental protection, viewing LNG as a relatively cleaner energy source than conventional fossil fuels (Das, Gangopadhyay, Bera, & Hossain, 2023). Nevertheless, the large-scale expansion of LNG exports may increase carbon emissions due to the production, transportation, and storage processes involved, thus underscoring the necessity for effective emission control policies. The existing literature also highlights the importance of adopting clean energy technologies and environmental regulatory mechanisms as central strategies for mitigating the adverse environmental impacts associated with the expansion of the LNG sector (Adekoya & Olabode, 2021).

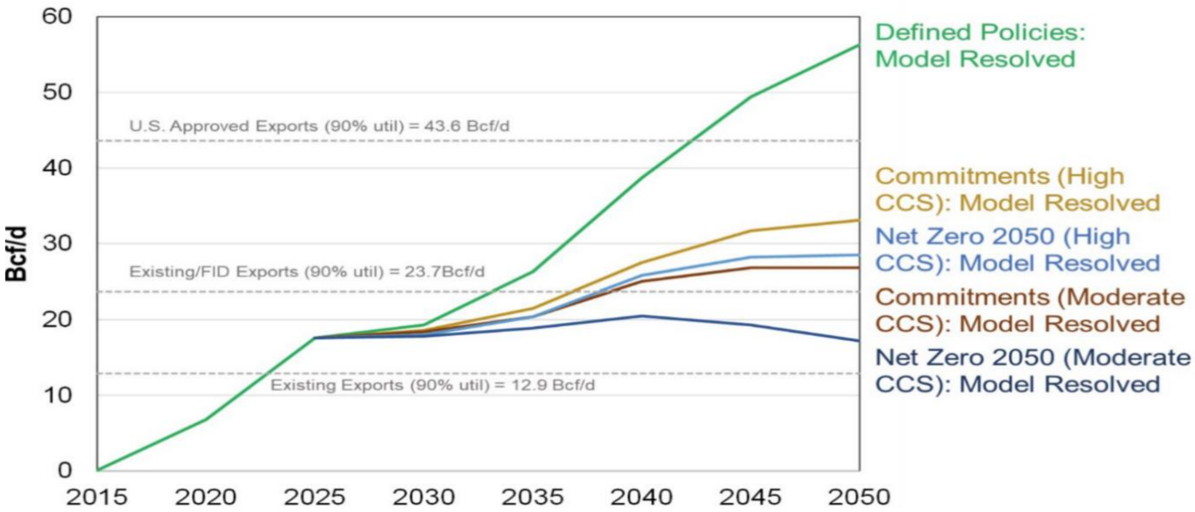
2.1. Future Global Demand for Natural Gas and U.S. LNG Exports

Accurately forecasting global demand for liquefied natural gas—and projecting the future scale of U.S. LNG exports—requires a comprehensive assessment of major supply sources, including their availability and pricing across different geographic regions. Both supply and demand are influenced by assumptions relating to public policy, as well as technological, social, and economic developments (Ali, Rahman, & Raihan, 2022; Chen, Rahaman, Murshed, & Mahmood, 2023).

Key determinants include natural gas prices, whether derived from domestic production, transported through pipelines, or shipped in liquefied form, alongside the prices of substitute energy sources available in global markets. Ultimately, these prices capture the complex interaction between market supply and demand dynamics, directly affecting consumption levels and, consequently, the scale of U.S. LNG exports (Fatima, Mentel, Dogan, & Hashim, 2022).

According to the U.S. Department of Energy (DOE, 2024), assigning relative probabilities to any of the proposed scenarios is unrealistic due to the multitude of influencing variables and the inherent complexity of future market dynamics. Figure 1 in the report illustrates the outcomes of five key scenarios, alongside current production capacity levels, capacities approved through final investment decisions, and authorized export capacities—which remained unaffected by the suspension of new permit issuances in 2024. These projections capture the overall trend in global demand for liquefied natural gas (LNG), characterized by a gradual and relatively modest increase up to 2030, followed by a pronounced acceleration in growth beginning around 2040.

Figure 1: U.S. Department of Energy Projections of LNG Exports According to Different Scenarios



Source: Department of Energy, with graphics by OnLocation.

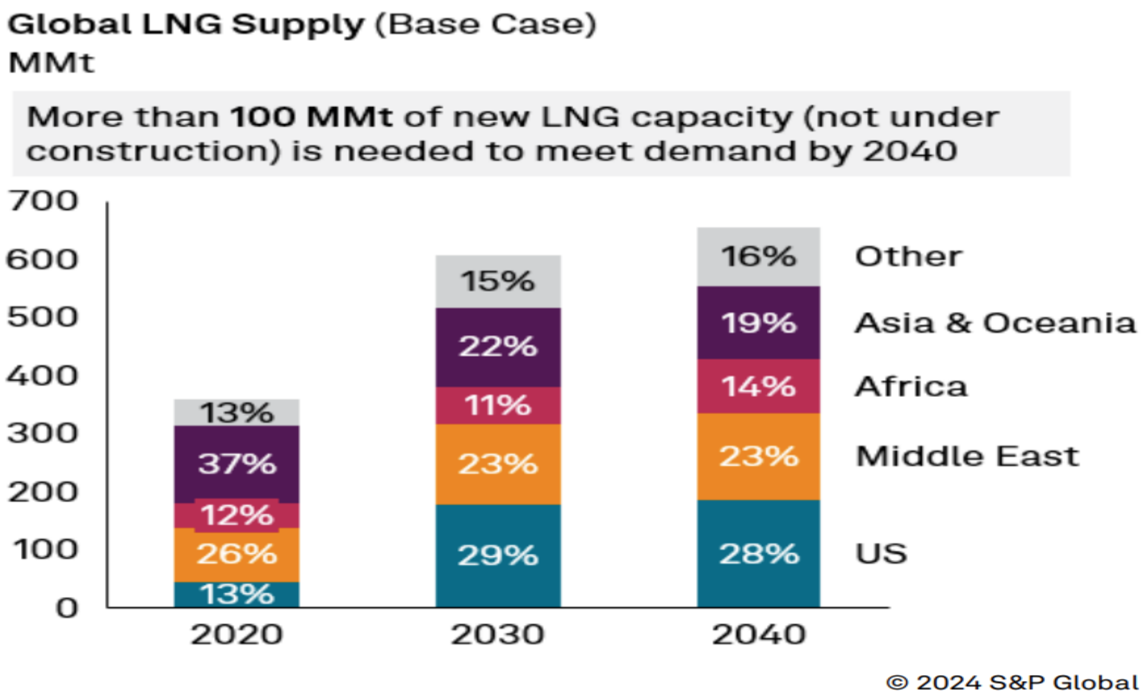
This figure illustrates the U.S. Department of Energy's projections for liquefied natural gas (LNG) exports through 2050, based on five main policy and modeling solution scenarios. The colored curves display the evolution of export volumes, measured in billion cubic feet per day (Bcf/d), across several levels of production and export capacity (DOE, 2024).

The **Adopted Policies Scenario** (green line) shows a notable upward growth trajectory after 2035, with exports reaching high levels by mid-century. The **Commitments with High Carbon Capture Scenario** (gold line) indicates sustained growth in exports, supported by the positive effects of expanding carbon capture projects (Lu, Jacob, Zhang, Shen, & Sulp, 2023). In contrast, the **Net-Zero Emissions by 2050 with High Carbon Capture Scenario** (blue line) projects gradual growth followed by stabilization or slight decline beyond mid-century. The **Commitments with Medium Carbon Capture Scenario** (brown line) represents an intermediate path between other cases, while the **Net-Zero Emissions by 2050 with Medium Carbon Capture Scenario** (dark blue line) suggests limited growth followed by a potential decline due to increasingly stringent climate regulations (Omara, Zavala-Araiza, Lyon, & Hmiel, 2022).

The horizontal gray lines represent the current production capacity, capacity approved through final investment decisions, and authorized export capacity. The figure provides a forward-looking projection of U.S. liquefied natural gas (LNG) export growth, formulated under varying assumptions regarding climate policy measures and technological progress in carbon capture and storage (CCS) systems. Export growth is anticipated to proceed gradually until around 2030, followed by a more rapid expansion across most scenarios—particularly under policy continuity without the introduction of additional regulatory constraints (Prest, 2024).

2-2. S&P Global LNG Supply Projections

Figure 2: S&P Global projections of global liquefied natural gas supply.



Source: S&P Global. MMT = million metric tons.

S&P Global's analysis reveals that U.S. liquefied natural gas (LNG) export supply in 2030—assuming no interruption in the issuance of construction permits—is projected to exceed the estimates provided by the U.S. Department of Energy (DOE). This finding implies that a continued suspension of permit approvals could exacerbate short-term supply constraints in the global LNG market. S&P estimates that U.S. LNG supply will reach approximately 24 billion cubic feet per day (Bcf/d) by 2030, a figure closely aligned with the production capacity already authorized by the DOE and approved for construction under final investment decisions (FID). Considering the extended timelines required to construct and operationalize LNG liquefaction plants and to obtain necessary regulatory approvals, further delays in permit issuance are likely to result in financial setbacks and lost investment opportunities.
Conversely, the DOE projections indicate supply levels below the capacity approved under FID through 2030, thereby allowing sufficient flexibility to meet expected demand, as outlined in its analysis (Sherwin, Rutherford, Zhang, & Che, 2024). Nevertheless, the outlook diverges beyond 2040: the DOE anticipates a substantial increase in U.S. LNG supply, contingent upon staying within approved

production capacity limits, while S&P Global forecasts suggest that the U.S. market share will remain relatively stable at levels comparable to those projected for 2030.

2-3. Natural Gas Supply and Demand Projections

Table 1 provides a consolidated summary of the natural gas demand categories employed in the analyses conducted by the U.S. Department of Energy (DOE) and S&P Global, alongside the projections of the International Energy Agency (IEA). The IEA adopts a notably more cautious and measured position regarding the licensing of liquefied natural gas (LNG) projects. For the sake of analytical consistency, all estimates have been standardized to a common unit—billion cubic feet per day (Bcf/d)—to enable robust comparison across sources. Notably, the IEA forecasts reflect a more conservative perspective on global LNG demand relative to the projections developed by both the DOE and S&P Global.

Table 1: **Comparative forecasts of natural gas supply and demand as reported by the U.S. Department of Energy (DOE), S&P Global, and the International Energy Agency (IEA).**

Year	2020	2030	2040
Global gas demand			
DOE (Defined Policies	390	410	470
case S&P Global (base	360	410	430
IEA (Stated Policies Scenario	(in 2022) 350	360	350
Global LNG demand			
DOE	56	87	124
S&P Global	48	81	87
(IEA (2023	53	67	73
US LNG supply			
DOE	7	19	39
S&P Global	6	24	25

Sources: Department of Energy (DOE), S&P Global, International Energy Agency (IEA), and authors' calculations.

Based on Table 2, the liquefied natural gas (LNG) market is undergoing complex and dynamic transformations in the balance between supply and demand, driven by multiple interrelated factors. Projections for 2025 indicate that LNG imports in certain regions are expected to increase by around 10% following a temporary downturn anticipated within the same year. This trend suggests a globally balanced expansion between supply and demand, which continues to support upward pressure on prices—particularly across European and Asian markets. The underlying growth is attributed to the combined influence of geopolitical developments and shifting climatic patterns that have heightened gas consumption in heating and industrial sectors.

On the supply side, production capacity is expanding significantly, supported by the commissioning of new projects—especially in North America and the Middle East—and the emergence of new exporters such as Canada, which has recently begun shipping LNG from newly completed facilities (DOE, 2024). Regarding demand, the Asian region remains the world's primary LNG consumer (Chien, Hsu, Ozturk, & Sharif, 2022), maintaining its leading role due to robust economic growth and growing attention to the transition toward more sustainable energy sources. The Middle East also continues to play a pivotal role in the LNG market, with a notable increase in import volumes (Mrabet, Alsamara, Mimouni, & Mnasri, 2021).

Currently, the LNG market is characterized by both cooperation and competition among the major suppliers—the United States, Qatar, and Australia—which collectively account for approximately 60% of global LNG exports. Geopolitical and economic developments in Europe—particularly the decline in Russian gas supplies—continue to exert a strong influence over market dynamics.
Furthermore, the global LNG sector has recently experienced a surge in large-scale strategic partnerships and investment initiatives, which are expected to reinforce market growth in the medium to long term and consolidate LNG's position as a key pillar of the global energy mix (Zhang, Gautam, Pandey, & Omara, 2020).

Table 2: Major LNG-exporting countries and corresponding natural gas production volumes.

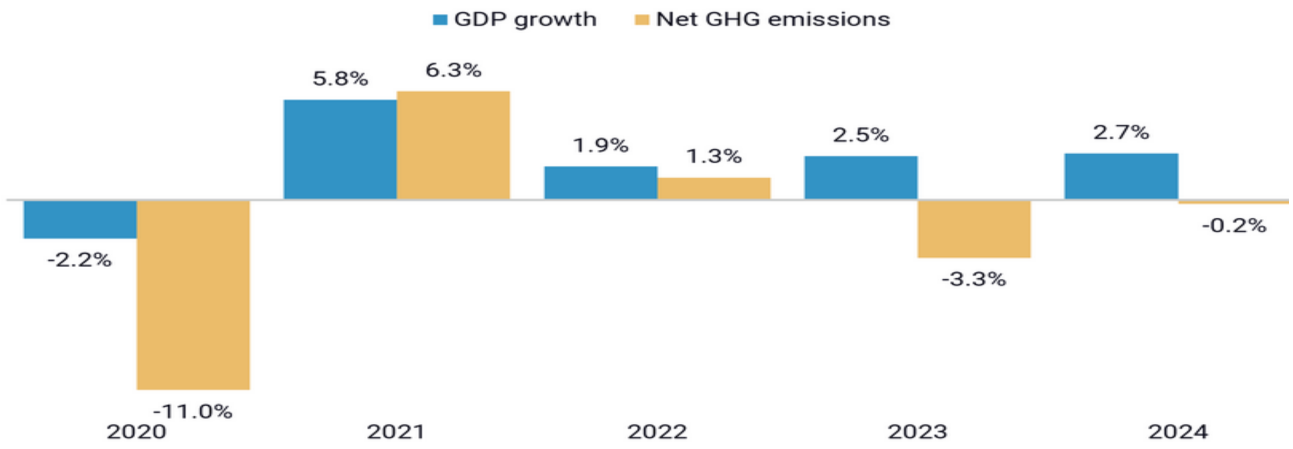
Country	(LNG Export (MT	Change in Rank from 2021	Natural Gas Production (MT)
Australia	80.90	-	117.50
.The U.S	80.50	1 □⬆	744.70
Qatar	80.10	1 □⬇	123.30
Russia	33.00	-	506.90
Malaysia	27.30	-	55.10
Indonesia	15.70	-	41.80
Nigeria	14.70	-	29.30

Sources:IGU world LNG report 2023 , enerdata-world energy& climate statistics Book 2023

2-4. Economic Growth and Marginal Reduction in Emissions in 2024

Economic growth remains a principal determinant of greenhouse gas emission levels (Fu, Gong, Zhao, & Chang, 2023). In 2024, the U.S. gross domestic product (GDP) expanded at an estimated annual rate of 2.7%, driven by robust consumer spending and substantial public and private investment. This performance persisted despite macroeconomic headwinds, including ongoing inflation, elevated interest rates, and increasing labor and material costs (Huang, Kuldasheva, Bobojanov, & Djalilov, 2023). A significant component of this growth stemmed from advancements in clean technology (Jung, Kim, Kang, & Jeong, 2022), with investment in the production and deployment of clean energy technologies comprising approximately 5% of total private investment in structures, equipment, and durable goods during the third quarter, according to data from the Rhodium Group's *Clean Investment Monitor* and the MIT Center for Energy and Environmental Policy Research (CEEPER).
Despite this economic momentum, preliminary estimates suggest a slight decline in overall U.S. greenhouse gas emissions in 2024 (Liu, Wang, Zhang, & Kong, 2019). The Environmental Protection Agency (EPA) is expected to publish the finalized 2024 Greenhouse Gas Inventory Report in the spring of 2026, following its annual data reconciliation. Based on early economic and energy consumption indicators, emissions are estimated to have decreased by a marginal 0.2% during 2024, positioning total U.S. emissions approximately 20% below 2005 levels and 8% lower than pre-pandemic levels.

Figure 3: Change in U.S. Gross Domestic Product and Net Greenhouse Gas Emissions.



Sources: Department of Energy (DOE), S&P Global, International Energy Agency (IEA), and authors' calculations.

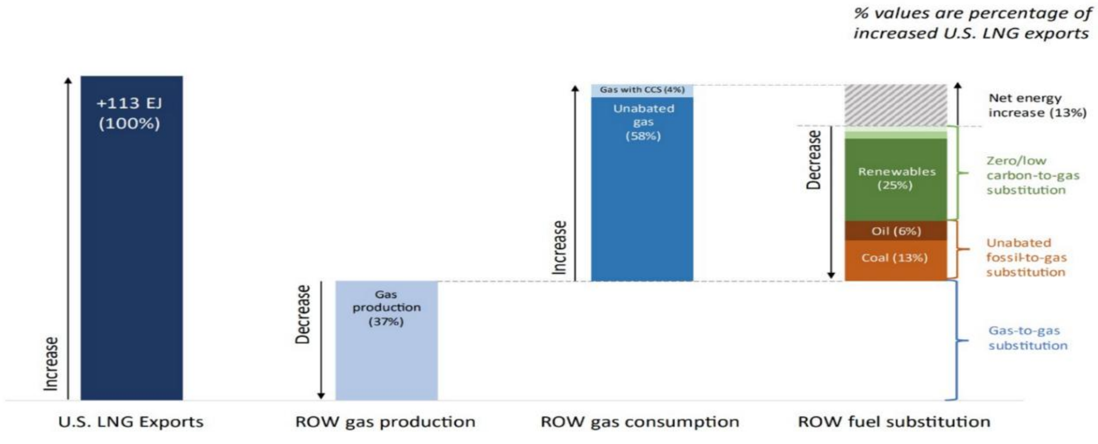
2-5. Substitution Effects of U.S. LNG Exports

Conceptually, given the price of imported liquefied natural gas (LNG) and the gas distribution network within a specific country, the effects of expanding U.S. LNG exports can unfold along several pathways. The first involves additional gas supplies from the United States entering the global market and partially displacing imports from other exporting countries. The impact of this substitution on greenhouse gas emissions depends on the relative supply chain emission intensity of U.S. LNG compared with that of the countries whose exports it replaces (Sherwin, Rutherford, Zhang, & Che, 2024).

For instance, replacing Russian or Algerian LNG with U.S. LNG could potentially reduce emissions if methane leakage rates in those countries are higher—provided that the additional emissions associated with liquefaction, shipping, and regasification are considerably lower than those linked to pipeline transport from the replaced suppliers to end consumers. Conversely, LNG sourced from Qatar is generally characterized by lower emissions and cleaner processing, which alters the substitution effect assessment in such cases (Chien, Hsu, Ozturk, & Sharif, 2022).

A recently published study by Robert Howarth (2024) represents one of the most influential—and controversial—contributions to the debate on LNG emissions. An earlier version of this study faced substantial criticism, including a detailed review by Jonah Messinger of the Breakthrough Institute, who highlighted methodological weaknesses in the analysis. Notably, Howarth's research reached a conclusion that contrasts with conventional understanding: it suggested that the carbon footprint of U.S. LNG exports exceeds that of coal by approximately 33%, posing a significant challenge to prevailing assumptions about the environmental benefits of natural gas (DOE, 2024).

Figure 4: U.S. Department of Energy assessment of the substitution effects of U.S. LNG exports.



Source: Department of Energy, with graphics by OnLocation.

The U.S. Department of Energy's assessment of liquefied natural gas (LNG) export pathways, as shown in Figure 4, projects a cumulative increase in U.S. LNG exports between 2020 and 2050 totaling 113 exajoules—representing the overall energy content of exports during this period. The analysis suggests that approximately 37% of U.S. LNG exports substitute for natural gas production in other countries, whereas the remaining 63% contributes to net growth in global natural gas consumption. Notably, only a small portion of this additional consumption—around four percentage points—utilizes carbon capture and storage (CCS) technology.
With respect to energy displacement, an estimated 13% of total U.S. LNG exports replace coal, 6% replace oil, and another 13% is linked to increased aggregate energy use. Furthermore, based on zero-carbon energy economic datasets, including nuclear power, more than 25% of the displaced energy is replaced by zero-emission energy sources (Voumik, Mimi, & Raihan, 2023).

Table 3: **Patterns of Liquefied Natural Gas (LNG) Substitution According to Assessments by the U.S. Department of Energy (DOE) and S&P Global.**

Pathway	2050–DOE (2020 (cumulative	S&P Global (2028–2040 yearly average)
Decreased ROW (Rest of World) natural gas production	%37	LNG, 14% other %35
eIncreased gas us	%13	No estimate provided
Decreased coal	%13	%23
Decreased oil	%6	%13
Decreased renewables, nuclear, others	%31	%15

Sources: Department of Energy, S&P Global, authors' calculations.

In total, the analysis forecasts a cumulative rise in carbon dioxide equivalent (CO_2 e) emissions of approximately 710 million metric tons between 2020 and 2050. These results indicate that the continuation of current practices could constitute a significant environmental concern (Zhang, Gautam, Pandey, & Omara, 2020). Nonetheless, it is important to note that this projected increase accounts for only about 0.05% of the estimated cumulative global CO_2 e emissions over the same period, as reported in Table 3 of the executive summary of the U.S. Department of Energy's report.

2-6- The most important economic literature of the past:

***Gilbert and Sovacool (2024),** in their study titled *"U.S. LNG Exports: Global Climate Revival or Collapse?"*, conducted a comprehensive analysis of the global greenhouse gas (GHG) emission impacts associated with the expansion of U.S. liquefied natural gas (LNG) exports. The study employed a hybrid methodological framework combining life cycle assessment and energy systems analysis, applied to panel data encompassing major Asian markets such as China, Japan, India, and South Korea.
The main findings reveal that the environmental impacts of U.S. LNG exports vary significantly depending on the energy substitution scenarios in importing countries. Specifically, replacing coal with natural gas was found to produce a substantial reduction in emissions, whereas substituting low-carbon energy sources—such as nuclear or renewable energy—resulted in an overall increase in total emissions. The study also underscored the critical role of infrastructure-related factors, particularly methane leakage occurring during production, transportation, and liquefaction processes. It argued that the expansion of U.S. LNG exports may contribute to higher global energy consumption, potentially leading to an overall

rise in emissions rather than a reduction, especially in the absence of effective and coordinated international climate mitigation policies.

In its conclusion, the study emphasized the necessity of conducting detailed and comprehensive evaluations prior to the approval of LNG export projects. It recommended considering all potential substitution-effect scenarios, strengthening technologies aimed at reducing methane leakage, and advancing the development and implementation of integrated and effective international climate policies (Gilbert & Sovacool, 2024).

*The study conducted **by Robert Howarth (2024)** offered an in-depth analysis of the greenhouse gas emissions associated with U.S. liquefied natural gas (LNG) exports, sparking wide debate within the scientific community due to its methodological approach and underlying assumptions. The researcher utilized an updated dataset to estimate methane and carbon dioxide emissions across the full life cycle of LNG production and liquefaction, with a particular emphasis on emissions occurring during extraction, transportation, and processing stages—rather than focusing solely on end-use combustion emissions. The findings revealed that the carbon footprint of U.S. LNG exports exceeds that of coal by approximately 33%, based on the 20-year Global Warming Potential (GWP20) metric. The study argued that previous assessments underestimated methane leakage, drawing upon recent atmospheric data indicating higher leak rates throughout the supply chain.

However, independent evaluations suggested that Howarth's estimates were likely overstated, with LNG-related emission values exceeding those commonly accepted in the scientific literature by 30% to 84%, depending on the scenario used. Although the study contributes valuable insights by emphasizing the need to update and refine methane leakage data within life cycle analyses, methodological limitations—such as allocation inconsistencies and reliance on thermal rather than electrical energy comparisons—introduce challenges in both accuracy and objectivity. As a result, the study's conclusions do not fully represent the current industrial conditions or prevailing scientific consensus (Howarth, 2024).

*The study **by Brynolf et al. (2018)** presented a comprehensive assessment of the environmental impact associated with the maritime transportation of various fossil and renewable fuels, with particular focus on comparing greenhouse gas (GHG) emissions from liquefied natural gas (LNG) transport and conventional fossil fuels. The researchers employed a Life Cycle Assessment (LCA) methodology to conduct a full supply chain analysis encompassing all stages—from raw material extraction and processing, through liquefaction and long-distance marine transport, to final delivery and distribution. The study's findings indicate that LNG transportation can offer relative environmental advantages under certain market conditions and technical scenarios, particularly in terms of reducing carbon dioxide emissions during shipping and maritime transport stages. However, the analysis also revealed tangible environmental risks arising from methane leakage during critical phases such as extraction, liquefaction, and cargo handling. These leaks can significantly influence total emission levels, since methane is a much more potent greenhouse gas than carbon dioxide over both short- and medium-term time horizons. The study concludes by emphasizing the need to enhance monitoring technologies and reduce methane leakage throughout the LNG supply chain. It also recommends integrating sustainable transport solutions to minimize the overall carbon footprint of LNG shipping, thereby fostering a more environmentally and economically sustainable balance within the global energy sector (Brynolf, Taljegard, Grahn, & Hansson, 2018).

*The report by **Rogelj et al. (2021),** issued by the Intergovernmental Panel on Climate Change (IPCC), serves as one of the principal references for understanding the challenges of reducing greenhouse gas emissions across various economic sectors, with particular emphasis on the energy sector as the largest contributor to such emissions. Regarding liquefied natural gas (LNG), the report highlights the importance of minimizing emissions associated with its use through the adoption of advanced technologies, including carbon capture and storage (CCS) solutions and enhanced energy efficiency across all stages of the value chain—from extraction and liquefaction to transportation and end-use consumption.

The report further underscores the pivotal role of technological innovation, encompassing the development of cleaner transport systems, improved methane leakage monitoring, and broader deployment of renewable and low-carbon nuclear energy sources to gradually reduce dependence on natural gas. Additionally, it stresses the need for the implementation of stricter climate policies at both national and international levels to reinforce emission reduction commitments. The report advocates for greater international cooperation in knowledge and technology exchange, increased financial support for sustainable energy projects, and special prioritization of developing and emerging economies in global climate action.

In summary, Rogelj et al. (2021) present a comprehensive framework illustrating how LNG can contribute to the transition toward a low-carbon energy system through technological advancement, sound policy implementation, and strengthened international cooperation. The report emphasizes that achieving global climate goals requires a delicate balance between technological innovation and political commitment to safeguard the climate and mitigate the environmental risks associated with fossil fuel use (Rogelj, 2021).

*The study by **Nossa and Teixeira (2020)** focused on modeling the life cycle assessment (LCA) of the liquefied natural gas (LNG) supply chain, offering an in-depth analysis of data uncertainty sources, particularly those related to methane leakage and emissions arising from liquefaction and shipping processes. The research employed advanced analytical methodologies to develop multiple scenarios that evaluate the effects of technological improvements in transportation processes and operational efficiency on the overall emissions associated with LNG.

The study provided a detailed examination of all stages of the supply chain, beginning with pipeline design and infrastructure, followed by liquefaction, storage, long-distance maritime transport using specialized carriers, and finally regasification at receiving terminals. It also addressed the challenges associated with monitoring and mitigating methane emissions at export and transport points, emphasizing the long-term environmental impact based on varying leakage rates.

The researchers highlighted the importance of adopting advanced technologies and precise monitoring systems to reduce emissions throughout the entire supply chain, while also stressing the need for sustainable operational strategies capable of improving the environmental performance of LNG operations. In doing so, the study offers a comprehensive scientific framework for understanding and optimizing processes aimed at reducing the carbon footprint of LNG and enhancing climate sustainability.

2-7- Research Gap:

The present study differs from previous research conducted on the U.S. economy by focusing on examining the impact of three independent variables—liquefied natural gas (LNG) exports, domestic natural gas production, and the gross domestic product (GDP) growth rate—on environmental quality, which serves as the dependent variable in this analysis. Although numerous empirical studies have analyzed the effects of LNG exports, domestic gas production, and economic growth on the environment and climate change in several advanced gas-exporting economies, there remains a clear gap in research that directly and comprehensively explores the relationship between these independent variables and environmental quality.

In recent years, scholarly attention has increasingly shifted toward investigating the effects of final energy consumption and climate change on economic growth. Moreover, a growing body of literature has examined the role of environmental policies in influencing foreign trade within the U.S. economy, underscoring the necessity of deepening the understanding of the interactions between economic and environmental factors in this context.

3. Measuring the Impact of Expanding LNG Exports on Environmental Quality in the United States

This section aims to analyze the effect of expanding LNG exports, domestic natural gas production, and economic growth on environmental quality in the United States. Environmental quality was measured using a carbon dioxide (CO_2) emissions indicator, with the study focusing on the energy sector—particularly liquefied natural gas—over the period from 1990 to 2022.

The Autoregressive Distributed Lag (ARDL) model was employed to evaluate both the short- and long-term relationships between CO_2 emissions and the expansion of LNG exports, based on comprehensive annual data for the same period. The study further assessed the separate effects of LNG export expansion, domestic natural gas production, and economic growth rate as independent variables on CO_2 emissions as the dependent variable. The chosen timeframe and country were determined by data availability, while also recognizing that the United States remains one of the economies most reliant on fossil fuels.

Table 04 variable descriptions and sources.

	Variables	Variables symbol	Musuring unit	Source
Dependent	Carbon dioxide emissions	CO2	T/J	The global economic
Independent	Liquefied Natural Gas (LNG) exports	LNG exports	Thousands of tonne	International energy agency
	Domestic natural gas production	PL gaz	Constant 2010 dollars	World bank
	Gross domestic product p/c	GDPPC	Constant 2010 dollars	World bank

Source: Authors' compilations

3-1- Model formulation:

To analyze the relationship between carbon dioxide emissions, the expansion of liquefied natural gas (LNG) exports, domestic natural gas production, and economic growth rate, the following equation was adopted::

$$CO2 = f(LNG\ exports,\ PL\ gaz\ ,GDPPC,)$$

3.1.1 - Results and Discussion:

The ARDL model is recognized as one of the most effective econometric techniques compared to alternative methods, making it well-suited for examining the impact of independent variables on a dependent variable.

3.1.2 - Results of Unit Root Tests:

Before conducting the ARDL bounds test on any variable, it is essential to verify its unit root properties. All variables must be stationary at either level I(0), first difference I(1), or a combination of both, in order to accurately determine the corresponding F-statistic. The stationarity of the series is assessed using both the Augmented Dickey-Fuller (ADF) test and the Phillips-Perron (PP) test to establish the order of integration.

Table -5 result of the augmented dickey fuller(ADF) and Phillips Peron (PP) unit root tests.

	ADF			PP			
	T-statistic	**p-value**	**Critical value**	**T-statistic**	**p-value**	**Critical value**	

CO2	5.628783	0.0005	3.565551	5.552255	0.0005	3.525643	I(1)
LNG exports	4.166540	0.0106	3.56883	4.552254	0.0116	3.525531	I(1)
GDPPC	4.178989	0.0018	2.968721	4.099222	0.0154	3.522543	I(1)
PL gaz	5.058744	0.0003	2.968781	4.885644	0.0024	3.562521	I(1)

Source: Authors' computations using Eviews 12 software.

The results of the Augmented Dickey-Fuller (ADF) test presented in Table 5 indicate that all five variables are stationary at the first difference I(1). Accordingly, the application of the Bound Testing approach is deemed appropriate for this study, with the Autoregressive Distributed Lag (ARDL) model considered the most suitable tool for analyzing the relationships among the variables.

3-1-3-Lag Order Selection Criteria :

After verifying that all variables were integrated of the same order, we proceeded in this step to identify the optimal lag length based on six different selection criteria, considering lags ranging from 0 to 2. The lag order was limited to a maximum of 2 due to the relatively small sample size.

Table 06 : Lag Order Selection Criteria Results

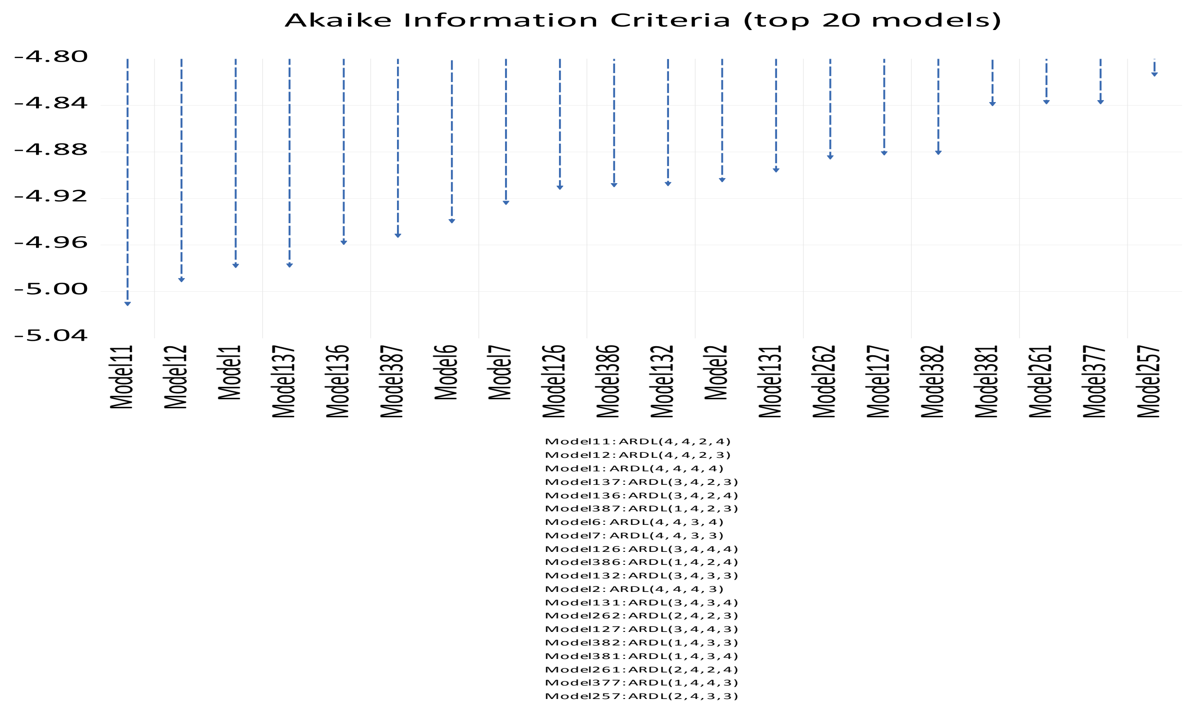
Lag	LogL	LR	FPE	AIC	SC	HQ
0	-1043.129	NA	1.01e+24	68.16922	67.40088	64.23503
1	-740.6954	240.5225*	2.35e+18*	59.74406*	60.14446*	54.24443*
2	-848.4533	28.82563	3.17e+18	59.94567	61.47456	54.74550

Source : Authors' computations using Eviews 12 software.

According to the LR, FPE, AIC, and SC criteria, the optimal lag length was determined to be 1. Subsequently, we proceeded to the Bounds test following the selection and diagnostic evaluation of the ARDL model, which was then followed by the Error Correction Model (ECM).

By applying the Automatic Lag Length Selection Test within the ARDL framework after determining the appropriate lag length, the Akaike Information Criterion (AIC) was employed to identify the optimal lag structure. Figure 05 illustrates the ARDL model estimation process with automatic lag selection using E-Views version 12. The selected model specification was (2, 4, 3, 4, 4), based on the lowest AIC value.

Figure 05 : Akaike Information Criteria.



Source: Authors' computations using Eviews 12 software

Figure 05 clearly indicates that the ARDL (2, 4, 3, 4, 4) model is the most suitable for our analysis.

3-2-Estimation of the ARDL model.

3-2-1-ARDL Bounds Test for Cointegration.

The bounds test is employed to assess the presence of a long-run equilibrium relationship among the variables within the ARDL model. According to the null hypothesis of no co-integration, if the calculated F-statistic falls below the lower critical bound, it signifies the absence of a co-integrating relationship. Conversely, if the F-statistic exceeds the upper critical bound, it provides evidence of a long-term cointegration linkage among the variables.

Table07 :result of ARDL bound test

Test statistic f-statistic	13.53933					
	10%		5%		1%	
Sample size	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
30	2.48	3.48	3.05	4.22	4.39	5.95
asymptotic	2.54	3.59	2.59	3.45	3.38	4.37

Source: Authors' computations using Eviews 12 software

Table 07 demonstrates that the calculated F-statistic value of 13.53933 exceeds the critical values at both I(0) and I(1) levels across the 1%, 5%, and 10% significance thresholds. Accordingly, there exists a cointegrating relationship among the variables within the study's model, indicating the feasibility of estimating an error correction model to investigate the short- and long-term effects of liquefied natural gas (LNG) exports, domestic natural gas production, and GDP per capita on carbon dioxide emissions.

3-2-2-Cointegrating ARDL Model Estimate.

The Autoregressive Distributed Lag (ARDL) model was employed to investigate the short- and long-term relationships among all variables, following the confirmation of their stability and cointegration.

The Empirical Results of ARDL Estimation

Table 08: Error Correction Model (ECM), Short-Run, and Long-Run Regression Results

ECM Regression, short-run

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D LNG exports	-0.130225	0.032506	-4.255751	0.0032
D(GDPPC)	37.87523	3.755254	14.81242	0.0000
D PL gaz	1623.154	528.3245	2.722542	0.0301
CointEq(-1)*	-1.449900	0.118422	-13.25313	0.0000
R-squared	0.972316	Mean dependent var	3456.172	
Adjusted R-squared	0.968757	S.D. dependent var	4250.646	
S.E. of regression	903.0356	Akaike info criterion	15.74722	
Sum squared resid	9775583.	Schwarz criterion	16.54473	
Log likelihood	-224.6777	Hannan-Quinn criter.	17.98824	
Durbin-Watson stat	2.664879			

* p-value incompatible with t-Bounds distribution

Long -run

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LNG exports	0.377390	0.025564	22.73295	0.0000
GDPPC	43.83552	2.455563	11.97862	0.0000
PL gaz	-3633.883	1136.407	-5.565006	0.0038
C	-45300.53	4597.506	-13.24483	0.0000

LNG exports= CO2 **-** (0.3773* **LNG exports**+ 43.83552*GDPPC -3633.8832* **PL gaz-** 45300.5314)

Source: Authors' computations using Eviews 12 software

In this study, the Error Correction Model (ECM) results revealed a negative coefficient for CointEq(-1) valued at -1.449, significant at less than 1%, confirming the existence of a long-term equilibrium relationship between the independent variables and carbon dioxide emissions. This indicates that long-term equilibrium is restored through the correction of short-term deviations at a rate of 144.9%. Moreover, the adjusted R^2 values for the long and short run were 0.9723 and 0.9687, respectively, demonstrating a strong model fit and the ability to explain approximately 97% of the variance in the independent variables.

In the short run, the ARDL estimation results indicate that the expansion of liquefied natural gas (LNG) exports and domestic natural gas production have a significant negative impact on carbon dioxide emissions, whereas GDP per capita exerts a significant positive effect on these emissions.

In the long run, the results reveal that both LNG exports and domestic natural gas production have a significant positive impact on carbon dioxide emissions, with GDP per capita also showing a substantial positive effect on emissions.

3-3-Arch test:

Engel (1982) developed the ARCH model to capture volatility clustering in time series data. The model's mean and variance equations are both conditional. The ARMA (p, q) process governs the conditional mean equation, which describes the generation of return series data. While the mean component models the systematic part of the data, the variance is dependent on the squared lagged residual terms.

Table 09: Arch test

Heteroskedasticity Test: ARCH			
F-statistic	0.547522	Prob. F(21,7)	0.8756
Obs*R-squared	0.056743	Prob. Chi-Square(1)	0.8233

Source: Authors' computations using Eviews 12 software

Table 9 indicates that the F-statistic associated with the ARCH test is 0.54, accompanied by a p-value of 0.87. Since this p-value exceeds the 5% significance level, we fail to reject the null hypothesis, thereby confirming the stability of the error term variance in the time series.

Table 10 Breusch-Godfrey Serial Correlation LM Test:

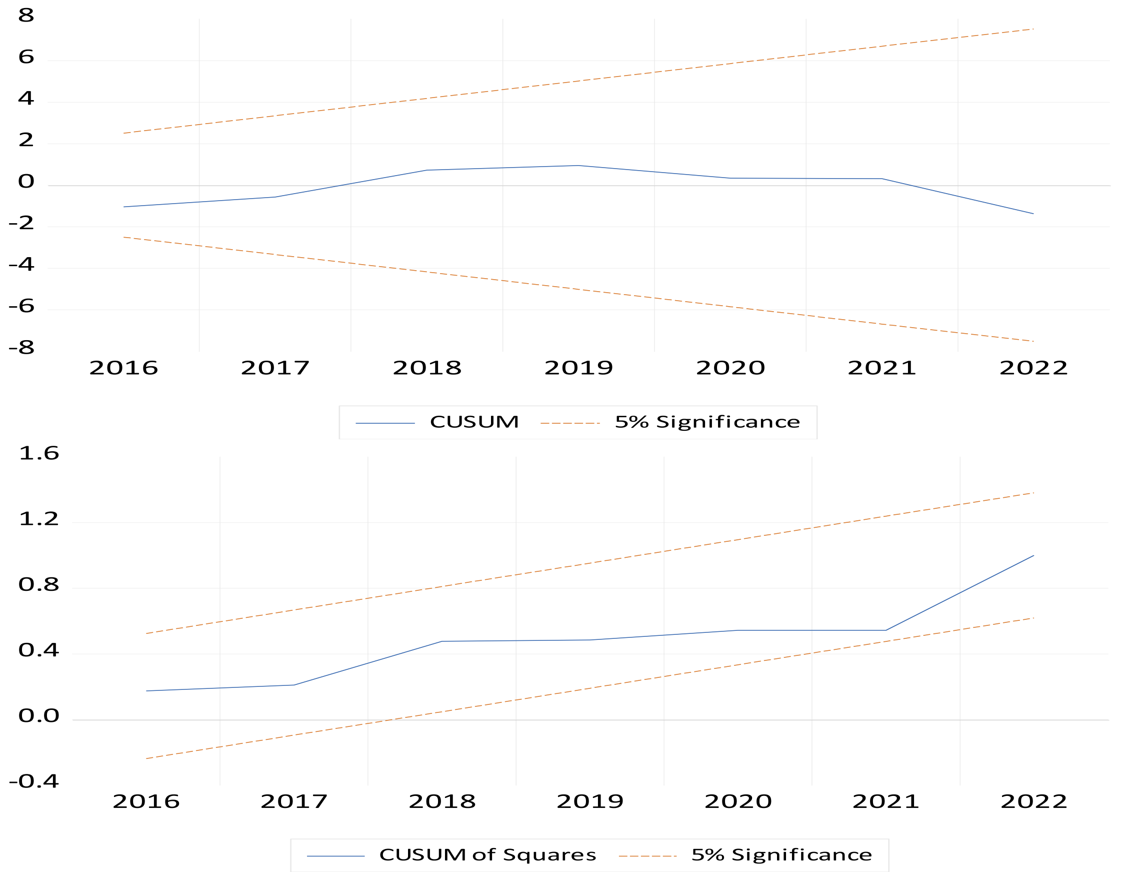
F-statistic	0.547226	Prob. F(21,7)	0.8644
Obs*R-squared	19.04674	Prob. Chi-Square(21)	0.6344
Scaled explained SS	1.094561	Prob. Chi-Square(21)	1.0000

Source: Authors' computations using Eviews 12 software

Table 10 presents an F-statistic value of 0.54, with the corresponding p-value of 0.86 exceeding the 5% significance threshold. Consequently, the null hypothesis is accepted, indicating the absence of autocorrelation among the error terms. This study employed two statistical tests: the CUSUM and CUSUM squared (CUSUM SQ) tests.

Furthermore, the CUSUM and CUSUM SQ tests were conducted to assess the model's stability, robustness, and structural integrity. These tests were originally introduced in standard statistical and economic literature by Brown et al. As illustrated in Figure 06, the model's stability is confirmed by the placement of the blue lines within the red boundaries, reflecting the significance level and stability of all coefficients in the error correction model.

Figure06: the cusum and cosum of Squares.

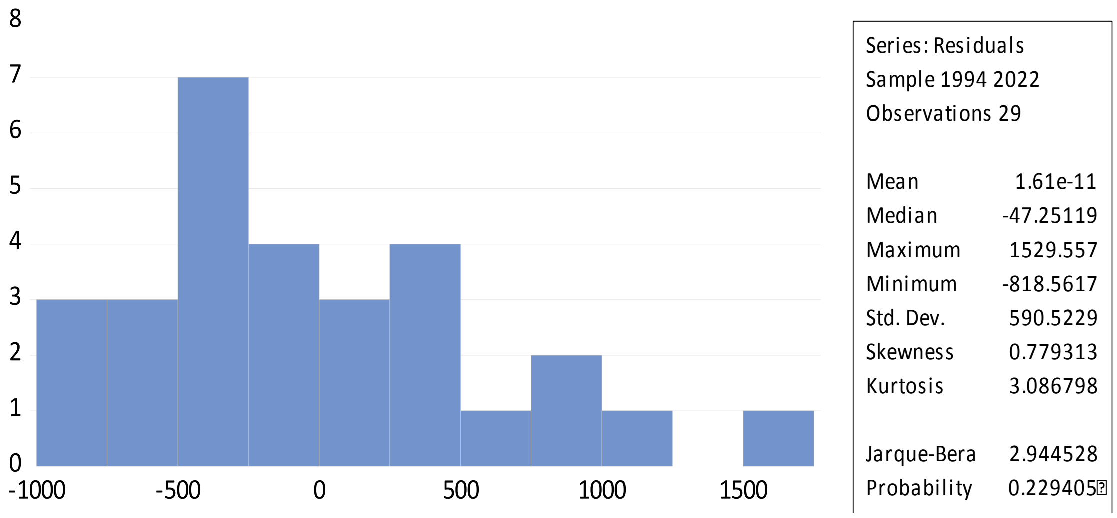


Source: Authors' computations using Eviews 12 software

"The figures respectively present the specifications and the outcomes of the CUSUM and CUSUM of Squares tests applied to the constructed models. In both graphs, the blue lines remain within the critical red boundaries, which confirms that the variables employed in the model exhibited stability throughout the period of investigation."

3-4-Normality test:

Figure07: Normality test



Source: Authors' computations using Eviews 12 software

The normality test, as depicted in Your Neighbour Pera's statistical figure, confirms that the residuals adhere to a normal distribution. This is supported by the statistical probability value of 2.94, which exceeds the conventional significance level of 0.05, thereby validating the assumption of normality for the residuals.

Conclusion

The expansion of liquefied natural gas (LNG) exports represents one of the most significant shifts in the global energy landscape, carrying far-reaching economic and social implications—particularly given the growing global demand for energy sources that are less polluting than coal. However, current scientific and academic evidence demonstrates that this expansion is not without substantial environmental challenges and raises increasing concerns about its impacts on local communities resulting from extraction, liquefaction, and export activities.

Studies indicate that the United States, through the application of hydraulic fracturing technologies and the large-scale production of shale gas, has achieved significant growth in LNG exports over the past decade. This has led to extensive development of liquefaction plants and large-scale infrastructure projects spanning the U.S. East and West Coasts as well as the Gulf region. Such expansion has been accompanied by a noticeable increase in air pollutant emissions, intensifying environmental concerns. Furthermore, the expansion of these facilities has exerted negative impacts on marine and coastal ecosystems, where associated chemical and thermal pollution has triggered fundamental environmental changes that threaten biodiversity and compromise the integrity of vital ecological systems in these regions.

It is important to note that the United States remains among the world's largest consumers of natural gas, meaning that domestic emissions have considerable implications for global carbon output. Rising natural gas prices—resulting from the expansion of LNG exports—are expected to reduce domestic gas demand, particularly in the energy sector. As coal continues to be phased out of the electricity market, it is likely that low-carbon sources such as renewable and nuclear energy will fill part of this gap. Consequently, the decline in domestic gas consumption driven by higher prices could contribute meaningfully to reducing carbon dioxide emissions at the national level.

The results of the long-run causal relationship test using the Vector Error Correction Model (VECM) revealed a bidirectional causal relationship between economic growth and the expansion of LNG exports, supporting the *feedback hypothesis*. The analysis also identified a mutual causal relationship between LNG export expansion and environmental degradation, as well as a two-way causal link between environmental degradation and economic growth. These findings reflect the complex interdependence and dynamic interactions among economic and environmental variables.

The current situation indicates that U.S. emission reduction efforts remain insufficient to meet the targets set under the Paris Agreement for 2030, which require emissions to be reduced by 50–52% compared with 2005 levels, and the more recent 2035 goal to reduce emissions by 61–66%. Achieving the 2030 target would necessitate an average annual reduction rate of approximately 7.6% between 2025 and 2030. For comparison, the year 2020 witnessed an 11% decline in emissions—the steepest on record—largely attributable to restricted mobility measures and the severe economic repercussions of the COVID-19 pandemic.

Recommendations

In light of the research findings revealing the dynamic and profound interconnections between economic growth, the expansion of liquefied natural gas (LNG) exports, and environmental degradation, this study offers a set of detailed recommendations aimed at achieving a sustainable balance between economic development objectives and environmental protection. These recommendations are presented within a rigorous and academically grounded framework as follows:

- ✓ The study recommends the development of advanced legislative frameworks focused on limiting emissions from the LNG sector, with the establishment of stringent standards aligned with the latest international protocols, particularly concerning greenhouse gases such as methane.
- ✓ It emphasizes the need for substantial investment in advanced technologies for carbon capture and storage (CCS) and the improvement of industrial efficiency in production and liquefaction processes to minimize harmful gas emissions to the lowest possible levels.
- ✓ The study advises the formulation of integrated development strategies that fundamentally incorporate the environmental dimension, ensuring that environmental and social impact assessments are embedded in the planning and decision-making stages of LNG export projects.
- ✓ It calls for the promotion of experimental and applied research focusing on the early detection of environmental problems resulting from LNG export expansion and the development of innovative, environmentally sound technological solutions.
- ✓ The study stresses the importance of ensuring active participation of local communities and affected stakeholders in the planning and implementation phases of LNG-related projects, guaranteeing the protection of human rights and the promotion of social equity.
- ✓ Finally, the study highlights the necessity of strengthening coordination of environmental policies and procedures between LNG-producing and consuming countries through international and regional agreements and initiatives aimed at knowledge exchange, emission standard harmonization, and collective action to combat climate change.

By effectively adopting and implementing these recommendations, it becomes possible to achieve a harmonious integration between economic expansion in the LNG sector and the preservation of essential environmental and public health standards. This approach supports sustainable development pathways, contributes to meeting internationally recognized climate goals, and ensures the long-term sustainability of natural resources and community well-being for future generations.

Bibliography:

Ali, A. Z., Rahman, M. S., & Raihan, A. (2022). Soil carbon sequestration in agroforestry systems as a mitigation strategy of climate change: A case study from Dinajpur, Bangladesh. Advances in Environmental and Engineering Research, 3(4), 1–15. https://doi.org/10.21926/aeer.2204056

Adekoya & Olabode & Rafi. (2021). Renewable energy consumption,carbon emissions and human development: Empirical comparison of the trajectories of world regions. Renewable Energy, Elsevier, vol. 179(C), pages 1836-1848. *https://DOI: 10.1016/j.renene.2021.08.019*

Department of Energy (DOE). 2024. Energy, Economic,and Environmental Assessment of U.S. LNG Exports. Washington, DC: DOE Office of Fossil Energy and CarbonManagement.

Raihan, A. (2023). Nexus between greenhouse gas emissions and its determinants: The role of renewable energy and technological innovations towards green development in South Korea. *Innovation and Green Development*, 2(3), 100066. https://doi.org/10.1016/j.igd.2023.100066

Howarth, R. W. (2024). Greenhouse gas emissions from LNG exports: A critical reassessment of climate impacts. [Preprint]. Cornell University.Available at: https://thebreakthrough.org/issues/energy/a-major-paper-on-liquified-natural-gas-emissions-is-riddled-with-errors

Yergin, D., C. Pascual, M. Stoppard, E. Eyberg, L. Caputo, M. Bonakdarpour, E. Kelly, et al. 2024. Major New US Industryat a Crossroads: A US LNG Impact Study—Phase 1. S&PGlobal. https://www.spglobal.com/en/research-insights/special-reports/major-new-us-industry-at-a-crossroadsus-lng-impact-study-phase-1

Al-Mulali, U., & Ozturk, I. (2015). The effect of energy consumption, urbanization, trade openness, industrial output, and the political stability on the environmental degradation in the MENA (Middle East and North African) region. Energy, 84, 382–389. *https://doi.org/10.1016/j.energy.2015.03.004*

Sherwin, E. D., J. S. Rutherford, Z. Zhang, Y. Chen, E. B.Wetherley, P. V. Yakovlev, E. S. F. Berman, et al. 2024. US Oil and Gas System Emissions from Nearly One Million Aerial Site Measurements. *Nature* 627 (8003): 328–34. https://doi.org/10.1038/s41586-024-07117-5

Prest, B. Forthcoming. Where does the marginal methane molecule come from? Implications of LNG exports for US natural gas supply and methane emissions. Working paper. Washington, DC: Resources for the Future. https://www.rff.org/publications/working-papers/where-does-themarginal-methane-molecule-come-from-implicationsof-lng-exports-for-us-natural-gas-supply-and-methaneemissions .

Alvarez, R. A., D. Zavala-Araiza, D. R. Lyon, D. T. Allen, Z. R. Barkley, A. R. Brandt, K. J. Davis, et al. 2018. Assessment of Methane Emissions from the U.S. Oil and Gas Supply Chain. *Science* 361 (6398): 186–88. https://doi.org/10.1126/science.aar7204

Akhbari, R., & Nejati, M. (2019). The effect of corruption on carbon emissions in developed and developing countries: empirical investigation of a claim. Heliyon, 5(9). *https://doi.org/10.1016/j.heliyon.2019.e02516*

Chen, X., Rahaman, M. A., Murshed, M., Mahmood, H., & Hossain, M. A. (2023). Causality analysis of the impacts of petroleum use, economic growth, and technological innovation on carbon emissions in Bangladesh. Energy, 267, 126565. https://doi.org/10.1016/j.energy.2022.126565

Chien, F., Hsu, C. C., Ozturk, I., Sharif, A., & Sadiq, M. (2022). The role of renewable energy and urbanization towards greenhouse gas emission in top Asian countries: Evidence from advance panel estimation Renewable Energy, 186, 207–216. https://doi.org/10.1016/j.renene.2021.12.118

Das, N., Gangopadhyay, P., Bera, P., & Hossain, M. E. (2023). Investigating the nexus between carbonization and industrialization under Kaya's identity: Findings from novel multivariate quantile on quantile regression approach. Environmental Science and Pollution Research. https://doi.org/10.1007/s11356-023-25413-x

Fatima, T., Mentel, G., Dogan, B., Hashim, Z., & Shahzad, U. (2022). Investigating the role of export product diversification for renewable, and non-renewable energy consumption in GCC (gulf cooperation council) countries: Does the Kuznets hypothesis exist? Environment, Development and Sustainability, 24(6), 8397–8417. https://doi.org/10.1007/s10668-021-01789-z

Fu, Q., Gong, Q., Zhao, X.-X., & Chang, C.-P. (2023). The effects of international sanctions on green innovations. Technological and Economic Development of Economy, 29(1), 141–164. https://doi.org/10.3846/tede.2022.17782

Huang, Y., Kuldasheva, Z., Bobojanov, S., Djalilov, B., Salahodjaev, R., & Abbas, S. (2023). Exploring the links between fossil fuel energy consumption, industrial valueadded, and carbon emissions in G20 countries. Environmental Science and Pollution Research, 30(4), 10854–10866. https://doi.org/10.1007/s11356-022-22605-9

Jung, S. H., Kim, H., Kang, Y., & Jeong, E. (2022). Analysis of Korea's green technology policy and investment trends for the realization of carbon neutrality: Focusing on CCUS technology. Processes, 10(3), 501. https://doi.org/10.3390/pr10030501

Liu, Q., Wang, S., Zhang, W., Li, J., & Kong, Y. (2019). Examining the effects of income inequality on CO2 emissions: Evidence from non-spatial and spatial perspectives. Applied Energy, 236, 163–171. *https://doi.org/10.1016/j.apenergy.2018.11.082*

Mrabet, Z., Alsamara, M., Mimouni, K., & Mnasri, A. (2021). Can human development and political stability improve environmental quality? New evidence from the MENA region. Economic Modelling, 94, 28–44. *https://doi.org/10.1016/j.econmod.2020.09.021*

Zhang, Y., R. Gautam, S. Pandey, M. Omara, J. D. Maasakkers, P. Sadavarte, D. Lyon, et al. 2020. Quantifying Methane Emissions from the Largest Oil-Producing Basin in the United States from Space. *Science Advances* 6 (17): eaaz5120. https://doi.org/10.1126/sciadv.aaz5120

Lu, X., D. J. Jacob, Y. Zhang, L. Shen, M. P. Sulprizio, J. D. Maasakkers, D. J. Varon, et al. 2023. Observation-Derived 2010-2019 Trends in Methane Emissions and Intensities from US Oil and Gas Fields Tied to Activity

Metrics. *Proceedings of the National Academy of Sciences* 120 (17): e2217900120. https://doi.org/10.1073/pnas.2217900120.

Omara, M., D. Zavala-Araiza, D. R. Lyon, B. Hmiel, K. A. Roberts, and S. P. Hamburg. 2022. Methane Emissions from US Low Production Oil and Natural Gas Well Sites. *Nature Communications* 13 (1): 2085. https://doi.org/10.1038/s41467-022-29709-3

Prest, B. Forthcoming.2024 Where does the marginal methane molecule come from? Implications of LNG exports for US natural gas supply and methane emissions. Working paper. Washington, DC: Resources for the Future. https://www.rff.org/publications/working-papers/where-does-themarginal-methane-molecule-come-from-implicationsof-lng-exports-for-us-natural-gas-supply-and-methaneemissions.

Sherwin, E. D., J. S. Rutherford, Z. Zhang, Y. Chen, E. B. Wetherley, P. V. Yakovlev, E. S. F. Berman, et al. 2024. US Oil and Gas System Emissions from Nearly One Million Aerial Site Measurements. *Nature* 627 (8003): 328–34. https://doi.org/10.1038/s41586-024-07117-5

Zhang, Y., R. Gautam, S. Pandey, M. Omara, J. D. Maasakkers,P. Sadavarte, D. Lyon, et al. 2020. Quantifying Methane Emissions from the Largest Oil-Producing Basin in the United States from Space. *Science Advances* 6 (17): eaaz5120. https://doi.org/10.1126/sciadv.aaz5120.

Voumik, L. C., Mimi, M. B., & Raihan, A. (2023). Nexus between urbanization,industrialization, natural resources rent, and anthropogenic carbon emissions in South Asia: CS-ARDL approach. Anthropocene Science. https://doi.org/10.1007/s44177-023-00047-3

Gilbert, A. Q., & Sovacool, B. K. (2024). US liquefied natural gas (LNG) exports: Boom or bust for the global climate? *Energy*, [Volume and issue if available], [Page numbers if available]. https://www.energy.gov/sites/default/files/2024-06/126.%20Gilbert,%20A.%20Q.%20&%20Sovacool,%20B.%20K.,%20US%20liquefied%20natural%20gas%20(LNG)%20exports.pdf

Brynolf, S., Taljegard, M., Grahn, M., & Hansson, J. (2018). Environmental assessment of fossil and renewable fuels transportation by ship and innovative energy carriers. *Journal of Cleaner Production*, 169, 115-123. https://www.sciencedirect.com/science/article/pii/S0959652618317388

Rogelj, J., et al. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/

Nossa, R., & Teixeira, A. P. (2020). Life cycle assessment of LNG supply chains: Modeling and uncertainty considerations. *Journal of Cleaner Production*, 263, 121429. https://doi.org/10.1016/j.jclepro.2020.121429