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Nuclear energy and carbon emissions: Dynamic ARDL simulation evidence from France (1970–2023)

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Abstract---This study investigates the dynamics of the relationship between nuclear energy consumption and greenhouse gas emissions in France over the period 1970–2023, employing the Dynamic ARDL Simulation framework. Based on 4,000 simulations distributed across 20 experiments and 10 time horizons, the results reveal the presence of asymmetric effects: while positive shocks of 0.25 and 0.5 standard deviations contribute to a reduction in emissions, negative shocks of the same magnitude lead to an increase. These findings confirm that integrating nuclear energy into the French energy mix represents an effective tool for reducing carbon emissions, while also highlighting the need to strike a balance between strengthening nuclear energy and expanding investments in renewable sources to ensure energy security and achieve long-term environmental sustainability goals.
Keywords---Nuclear energy consumption, Greenhouse gas emissions, Dynamic ARDL Simulation, Renewable energy, Environmental sustainability.
JEL Classification : C32, Q42, Q53, Q54

1 Introduction:

Climate change, primarily driven by rising greenhouse gas emissions, represents one of the most pressing environmental challenges of the twenty-first century. In this context, nuclear energy has emerged as a critical alternative to fossil fuels, offering the potential to reduce carbon dioxide (CO_2) emissions while ensuring a stable energy supply. Despite ongoing debates concerning safety, radioactive

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waste management, and economic feasibility, nuclear energy is widely recognized as a key component of low-carbon energy strategies (Hassan et al, 2024)

France stands as one of the most illustrative examples of large-scale reliance on nuclear power. Since the 1970s, nuclear energy has accounted for the majority of the country's electricity generation, positioning France among the lowest CO_2 emitters per unit of electricity in Europe. This extensive use of nuclear power underscores its role in shaping national carbon footprints and highlights the importance of energy mix choices in achieving climate goals (Kartal et al, 2023). Empirical evidence further suggests that increased nuclear energy use is generally associated with long-run reductions in CO_2 emissions, often alongside renewable energy deployment. In the French context, this relationship reinforces the argument that nuclear power remains a vital element of environmental sustainability strategies. At the same time, the complexity of the nuclear emissions nexus shaped by technological, political, and economic factors demands further attention to fully understand the long-term implications of nuclear energy for carbon mitigation (Ridwan et al, 2023).

Building on these considerations, the present study seeks to answer the following question: to what extent do shocks in nuclear energy consumption affect greenhouse gas emissions in France, while accounting for renewable energy consumption, GDP, and urbanization? It is expected that positive shocks in nuclear energy consumption will reduce emissions by limiting dependence on fossil fuels, whereas negative shocks will increase emissions due to substitution toward more polluting sources. To address this question, the study analyzes the long-term effects of nuclear energy consumption shocks on emissions over the period 1970–2023, tests the asymmetry of these impacts, compares the role of nuclear and renewable energy in France's decarbonization pathway, and contributes to ongoing debates on the capacity of nuclear power to reconcile energy security with environmental sustainability. Although numerous studies have explored the link between nuclear energy and emissions, the evidence remains fragmented and often inconclusive, particularly for highly nuclear-dependent economies such as France. Few investigations have examined long-horizon shocks within a dynamic framework that simultaneously incorporates renewables, GDP, and urbanization. By addressing this gap, the present study provides new insights into the asymmetric impacts of nuclear energy on emissions across five decades, thereby advancing the understanding of its role in achieving long-term climate goals.

2. Literature review

The relationship between nuclear energy and carbon emissions has been examined across engineering, policy, and econometric literatures. At the systems level, a consistent baseline finding is that nuclear electricity exhibits very low life-cycle greenhouse gas (GHG) emissions per kWh comparable to renewables because operational emissions are near zero and upstream fuel-cycle emissions are modest. The Intergovernmental Panel on Climate Change (IPCC) reports life-cycle values generally below ~40 gCO_2-eq/kWh for nuclear, supporting its role in mitigation portfolios (IPCC, 2007) (IPCC, AR5 WGIII, Chapter 7: Energy systems., 2014)

The role of nuclear energy in mitigating carbon emissions has been a subject of extensive research, particularly in countries with significant nuclear power generation like France. Studies indicate that nuclear power has substantially contributed to reducing France's carbon footprint. For instance, a report by the Institut Économique Molinari highlights that France's nuclear energy has prevented CO_2 emissions equivalent to 28 times the total emissions of 2023 over 47 years (Institut Économique Molinari, 2025) . Additionally, a life cycle assessment by Électricité de France (EDF, 2022)reveals that each kilowatt-hour of electricity produced by EDF's reactors emits less than 4 grams of CO_2, underscoring the low-carbon nature of nuclear energy (World Nuclear News). However, the impact of nuclear energy on carbon emissions is not without debate. Some studies suggest that while nuclear power reduces direct CO_2 emissions, the overall environmental footprint, including ecological impacts, may not be negligible (Soto & Xavier, 2024). Furthermore, the future role of nuclear energy in France's energy mix is influenced by policy decisions and technological advancements, such as the development of Small Modular Reactors (SMRs), which aim to provide low-carbon heat for industrial processes (Monde, 2024)

France provides an important reference case for studying this nexus. Owing to the large nuclear fleet built since the 1970s, nuclear power remains the dominant source of electricity and underpins one of the lowest-carbon power mixes among advanced economies. According to the International Energy Agency (IEA), nuclear supplied about 64% of France's electricity in 2023, contributing to a low emissions intensity of power generation (IEA, 2025). Sectoral statistics from industry and government sources echo this picture, attributing France's comparatively low per-kWh CO_2 intensity to the sustained contribution of nuclear alongside hydro and growing renewables (World Nuclear News, 2025).

Econometric evidence on the emissions impact of nuclear use, while sensitive to model choice and data, broadly finds a negative long-run association between nuclear electricity and CO_2 emissions. For France specifically (Kartal et al, 2023), analyze shocks to nuclear, gas, and coal consumption and show that increases in nuclear usage are associated with statistically significant reductions in CO_2 emissions, including under counterfactual scenarios mimicking gas supply disruptions. Multi-country studies similarly tend to find that higher nuclear shares correlate with lower emissions, though effect sizes vary with energy mix, policy regimes, and structural conditions (Ridwan et al, 2023) (Hassan et al, 2024)

Comparative policy research reinforces these econometric findings by examining natural experiments in nuclear policy. For example, modelling work on Germany's phase-out indicates that delaying shutdowns would have lowered short-term GHG emissions relative to a rapid exit, highlighting the substitution effect toward gas and coal when nuclear capacity is removed (Glynos & Hendrik , 2024). Such evidence underscores that the emissions consequences of nuclear depend critically on the marginal replacement technology and the flexibility of the broader power system.

The broader policy context in Europe has evolved to recognize certain nuclear activities as contributors to climate mitigation under specific conditions. In 2022, the European Commission's sustainable finance taxonomy included nuclear as a transitional activity, and in September 2025 the EU General Court upheld this inclusion against a legal challenge reflecting a view that nuclear can facilitate decarbonization when safety and waste criteria are met (European Commission, 2022) (Associated Press, 2025) (World Nuclear News, 2025). For France, this framing supports continued investment pathways, including life-extension of existing reactors and potential new build, while debates persist over cost, timelines, and governance.

At the same time, important caveats remain. Life-cycle assessments emphasize low median emissions for nuclear but acknowledge ranges that depend on uranium ore grades, enrichment routes, construction timelines, and decommissioning assumptions. Policy and economics literatures point to capital cost overruns, schedule delays, and financing risks factors that shape whether nuclear displaces fossil generation in practice. Furthermore, integration with renewables, grid flexibility, and demand-side measures determine the net emissions impact of nuclear additions or retirements. Hence, the literature converges on a conditional conclusion: nuclear power is a potent tool for reducing CO_2 emissions when embedded in a coherent system design and policy environment; France's experience exemplifies these dynamics, but generalization requires attention to country-specific constraints and opportunities (IPCC, AR5 WGIII, Chapter 7: Energy systems., 2014)

3. Data and Methodology

3.1 Variables and data

This study aims to investigate whether nuclear energy can effectively reduce carbon emissions by analyzing the impact of shocks in nuclear energy consumption. For this purpose, we use annual time series data spanning from 1970 to 2023 for France. This country was strategically chosen due to its unique position as a global leader in nuclear power, with nuclear energy consistently generating over 70% of its electricity since the early 1990s. This high dependency makes France a compelling case study for evaluating nuclear power's role as a low-carbon energy source. The chosen timeframe (1970–2023) is based on the availability of a long and comprehensive dataset that allows for robust econometric analysis, covering key periods of nuclear expansion and energy policy shifts. Table 1 provides detailed descriptions of the variables and their respective sources from Our World in Data and the World Bank, including Annual greenhouse gas emissions from fossil fuels and industry (TGHG), Primary energy consumption from nuclear power (NC), Primary energy consumption from renewables (RC), Gross Domestic Product (GDP), and Urban population (UP).

3.2 Model specification

This study enriches the ongoing scholarly debate on the environmental implications of nuclear energy by examining the long-term effect of nuclear power consumption shocks on greenhouse gas (GHG) emissions in France over the period 1970–2023. To address potential heteroscedasticity (Sarkodie & Owusu, 2020), the empirical strategy employs a log-linear specification in which all variables are transformed into their natural logarithms. The model is formally expressed as:

$$lTGHG_t = B_0 + B_1 lEN_t + B_2\, lRC_t + B_3\, lGDP_t + B_4\, lUP_t + \ \ U_t \ldots\ldots (2)$$

where $lTGHG_t$ denotes the natural logarithm of GHG emissions from fossil fuel combustion and industrial activities. The explanatory variables include lEN_t (nuclear energy consumption), lRC_t (renewable energy consumption), $lGDP_t$ (gross domestic product), and lUP_t (urbanization), while U_t captures unobserved disturbances. A negative coefficient for B_1would imply that an increase in nuclear power usage reduces emissions, underscoring its potential contribution to the low-carbon transition. To isolate the nuclear effect from other structural and demographic drivers, renewable energy, GDP, and urbanization are incorporated as control variables.

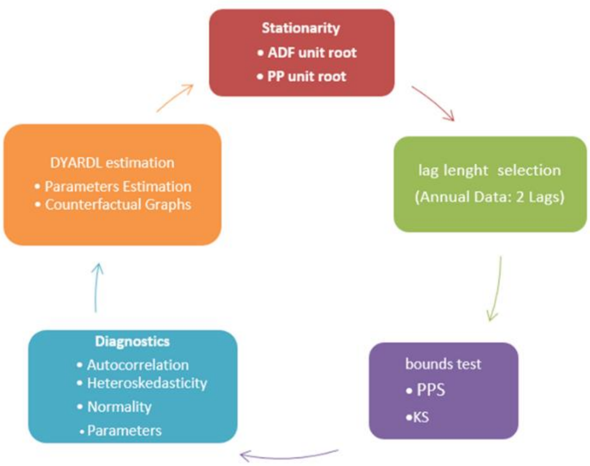

Fig. 1. Methodological flow chart

The empirical investigation proceeded in several stages. First, data characteristics were assessed through outlier detection and stationarity testing. Since both the conventional and dynamic Autoregressive Distributed Lag (ARDL) models require regressors to be integrated of order zero or one, I(0) or I(1), and the dependent variable to be strictly I(1) (Sam, McNown, & Goh, 2019) (Pata & Caglar, 2021), unit root tests were conducted using Augmented Dickey-Fuller (ADF) (Dickey & Fuller, 1981) and Phillips-Perron (PP) (Phillips & Perron, 1988) procedures. Subsequently, the conventional ARDL bounds-testing approach was applied to assess the existence of a long-run cointegrating relationship among the variables, with Narayan's (Narayan, 2005) critical values serving as benchmarks. To validate whether the identified relationship was genuine or spurious, the Kripfganz & Schneider (KS) (Kripfganz & Schneider, 2020)critical values and p-values were employed. In this phase, both the short-run and long-run effects of nuclear energy consumption on GHG emissions were estimated.

Finally, after ensuring that the estimated models satisfied standard econometric diagnostics, counterfactual shocks in nuclear power consumption were simulated using the dynamic ARDL framework. The ARDL methodology developed by Pesaran, M. H., Shin, Y., & Smith, R. J. (2001) (Pesaran, Shin, & Smith, 2001) is particularly advantageous given its ability to accommodate regressors of mixed integration orders and its robustness to limited sample sizes. However, as argued by Sarkodie et al. (Sarkodie et al, 2019), the dynamic ARDL simulation technique offers superior interpretive clarity by enabling the visualization of hypothetical changes in independent variables and their effects on the dependent variable. Accordingly, after confirming the reliability of the traditional ARDL estimates, dynamic ARDL simulations were implemented to assess the impact of nuclear energy shocks at ±0.25% and ±0.5%. These simulations were performed over 4,000 iterations with a 10-period horizon (t=10) for the projection period 2024–2054, strictly adhering to the methodological specifications recommended by Sarkodie to ensure analytical robustness. DARDL model is specified as follows:

$$\Delta LTGHG_t = \gamma_0 + \delta_0 LTGHG_{t-1} + \xi_1 LNC_t + \xi_2 LRC_t + \xi_3 LUP_t + \delta_1 LGDP_{t-1} + \phi_1 \Delta LGDP_t + \phi_2 \Delta LGDP_{t-1} + U_t$$

4. Results and Discussion

This study employs the Autoregressive Distributed Lag (ARDL) and Dynamic ARDL (DYNARDL) approaches to explore the short- and long-run interactions among nuclear energy consumption, renewable energy consumption, GDP, urbanization, and greenhouse gas (GHG) emissions in France over the period 1970–2023. Descriptive statistics (Table 2) reveal that LGDP exhibits the highest mean (28.187), whereas LRC records the lowest (5.383). Nuclear energy consumption (LNC) is characterized by the highest degree of volatility (1.252) and a leptokurtic distribution (kurtosis = 3.616), underscoring recurrent fluctuations in nuclear supply and demand. Skewness measures further indicate asymmetric distributions, with LRC and LUP being positively skewed, while LTGHG, LNC, and LGDP exhibit negative skewness. The Jarque–Bera test validates normality for all variables except LNC, which shows significant deviations, reflecting structural adjustments within France's nuclear sector.

The box plots (Figure 2) reveal the presence of several negative outliers in LNC, which are likely associated with periods of reduced nuclear energy production resulting from institutional reforms or technical constraints, while the other variables appear relatively stable over the study period. The correlation matrix (Figure 3) indicates a negative relationship between LTGHG and all explanatory variables, suggesting that higher levels of nuclear and renewable energy consumption, coupled with economic growth and urbanization, are associated with lower greenhouse gas emissions. These findings highlight the complementary role of both the energy transition and structural economic transformation in mitigating environmental degradation, thereby reinforcing the necessity of a causal analysis through ARDL estimations.

The Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests (Table 3) reveal heterogeneous integration orders: LRC, LTGHG, and LUP are integrated of order one, I(1), while LNC and LGDP are stationary at levels, I(0). This heterogeneity excludes the use of conventional cointegration techniques such as Johansen's approach and underscores the suitability of the ARDL framework, which accommodates both I(0) and I(1) variables within a unified model. Furthermore, the bounds test results (Table 4) confirm the existence of a long-run equilibrium relationship, as the F-statistic (8.130) surpasses the upper critical bounds across all significance levels. This finding is further reinforced by the t-Student statistic, validating the robustness of the identified equilibrium and confirming the appropriateness of ARDL in capturing both short- and long-run dynamics. These diagnostic outcomes provide a solid econometric foundation for advancing to ARDL estimations and dynamic simulations, thereby ensuring analytical rigor in assessing the impact of nuclear energy shocks on GHG emissions.

Long-run estimations (Table 5) reveal that nuclear energy consumption (LNC) and renewable energy consumption (LRC) exert significant negative effects on LTGHG, reducing emissions by 0.153% and 0.173%, respectively, for every 1% increase. Conversely, GDP (LGDP) positively influences emissions (coefficient = 1.519), supporting the Environmental Kuznets Curve (EKC) hypothesis. Urbanization (LUP) contributes to emission reductions (coefficient = -4.098), likely due to efficiency gains in urban infrastructure. Short-run dynamics captured by the DYNARDL model show that deviations from equilibrium adjust rapidly, with the error correction term (-0.411) indicating that approximately 41% of disequilibrium is corrected annually.

Diagnostic tests (Table 6) confirm the robustness of the model: there is no serial correlation, heteroscedasticity, or misspecification, and residuals are normally distributed. Stability checks via CUSUM and CUSUMSQ (Figures 4 and 5) further validate the long-run consistency of the model, reinforcing its reliability for policy implications. The dynamic ARDL simulations were conducted with a **1** standard deviation shock in nuclear energy consumption, using 4,000 iterations based on the median values, over a horizon of 10 time periods and 30 simulation replications.

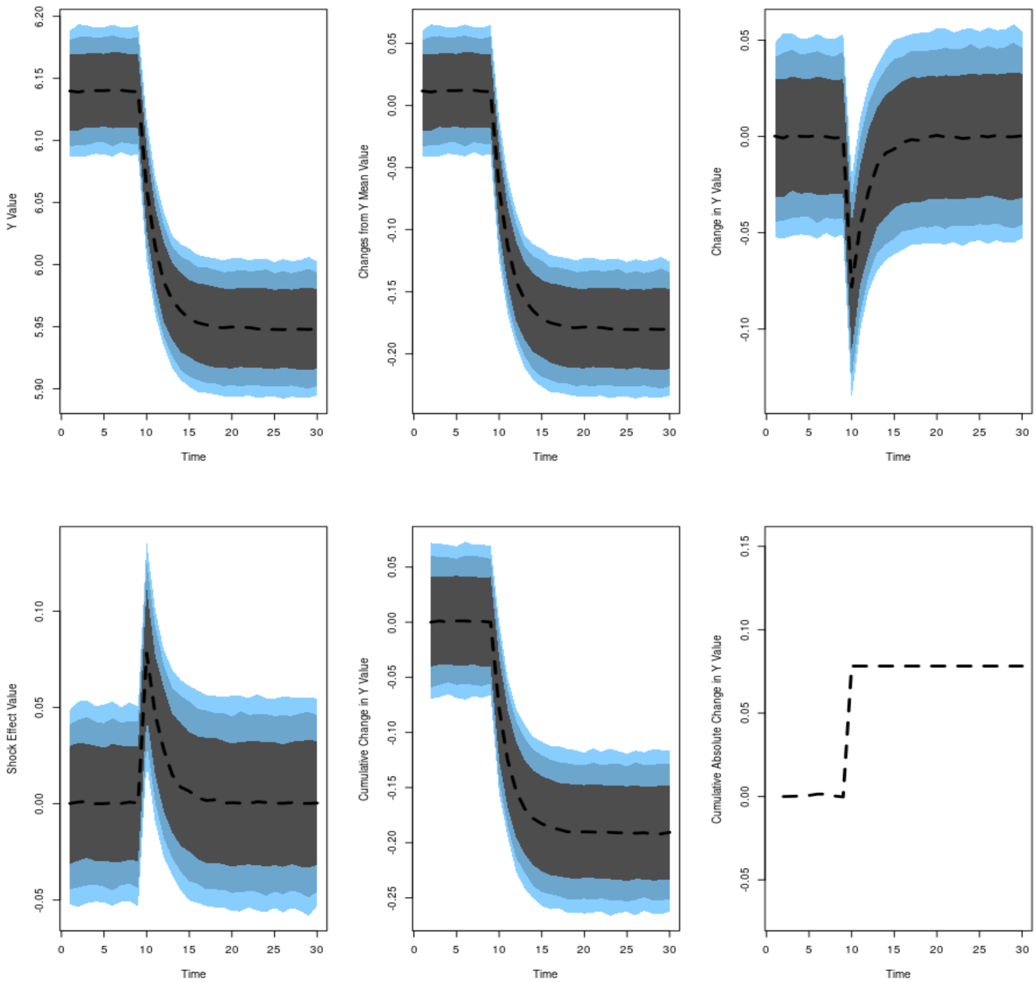

Fig. 6 Dynamic ARDL Simulation of a 1 SD Shock in Nuclear Energy Consumption (4,000 Iterations, Median-Based, 10-Period Horizon, 30 Replications).

The dynamic ARDL simulations were conducted with a **-1** standard deviation shock in nuclear energy consumption, using 4,000 iterations based on the median values, over a horizon of 10 time periods and 30 simulation replications.

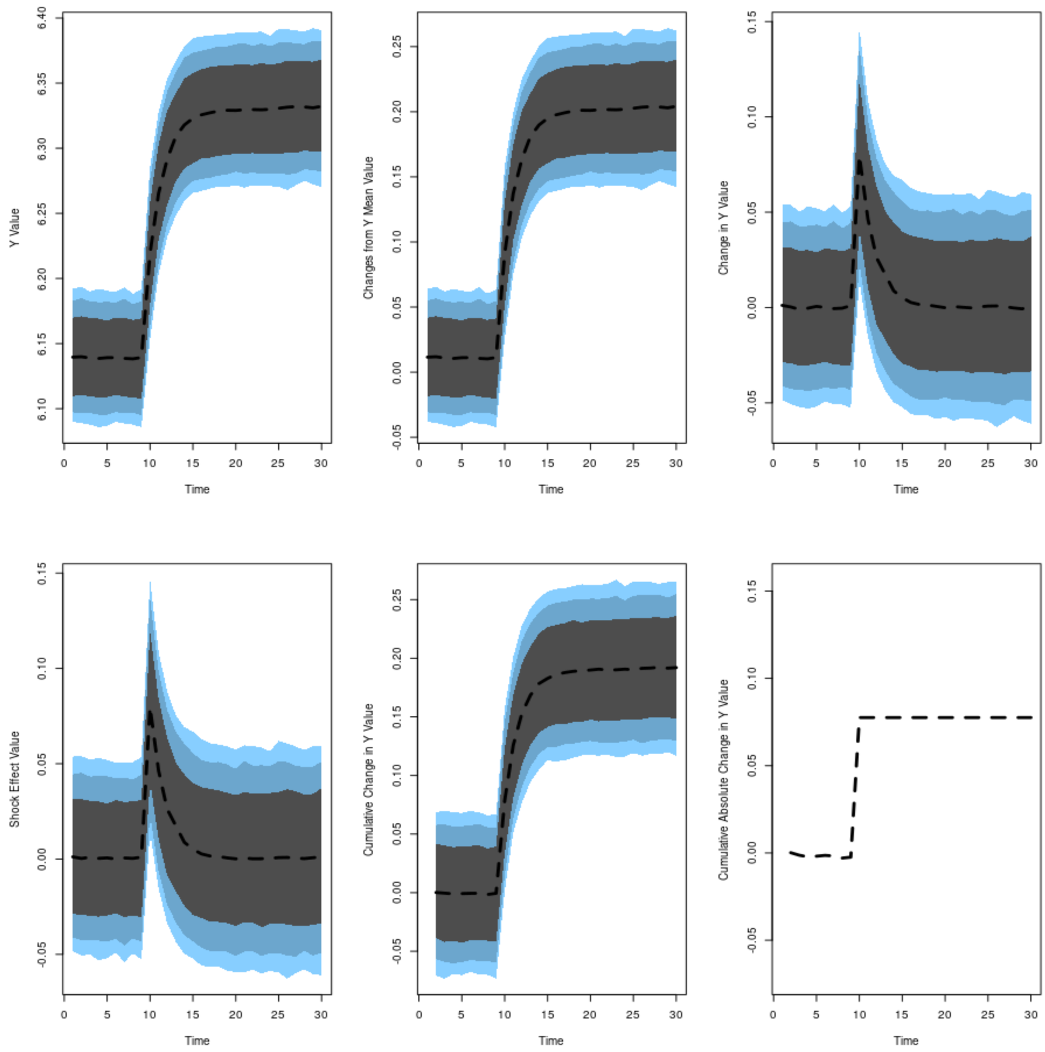

Fig. 7 Dynamic ARDL Simulation of a 1 SD Shock in Nuclear Energy Consumption (4,000 Iterations, Median-Based, 10-Period Horizon, 30 Replications)

The dynamic ARDL simulations with a +1 standard deviation shock in nuclear energy consumption, based on 4,000 iterations over 10 time periods and 30 replications, reveal a significant and persistent decline in greenhouse gas emissions. This result confirms the strong substitutive role of nuclear power in displacing fossil fuels, thereby reducing the overall carbon intensity of the French energy system.

In contrast, a −1 standard deviation shock produces an opposite trajectory: emissions increase markedly and stabilize at higher levels over the simulation horizon. This finding indicates that a contraction in nuclear energy use forces a shift toward more carbon-intensive energy sources, highlighting the vulnerability of the energy mix when nuclear supply is reduced. Taken together, these asymmetric responses reinforce the argument that nuclear energy acts as a stabilizing force in emission reduction, while its decline exacerbates environmental pressures. Consequently, the results underline the importance of maintaining and expanding nuclear capacity alongside renewable energy deployment to achieve long-term sustainability and energy security.

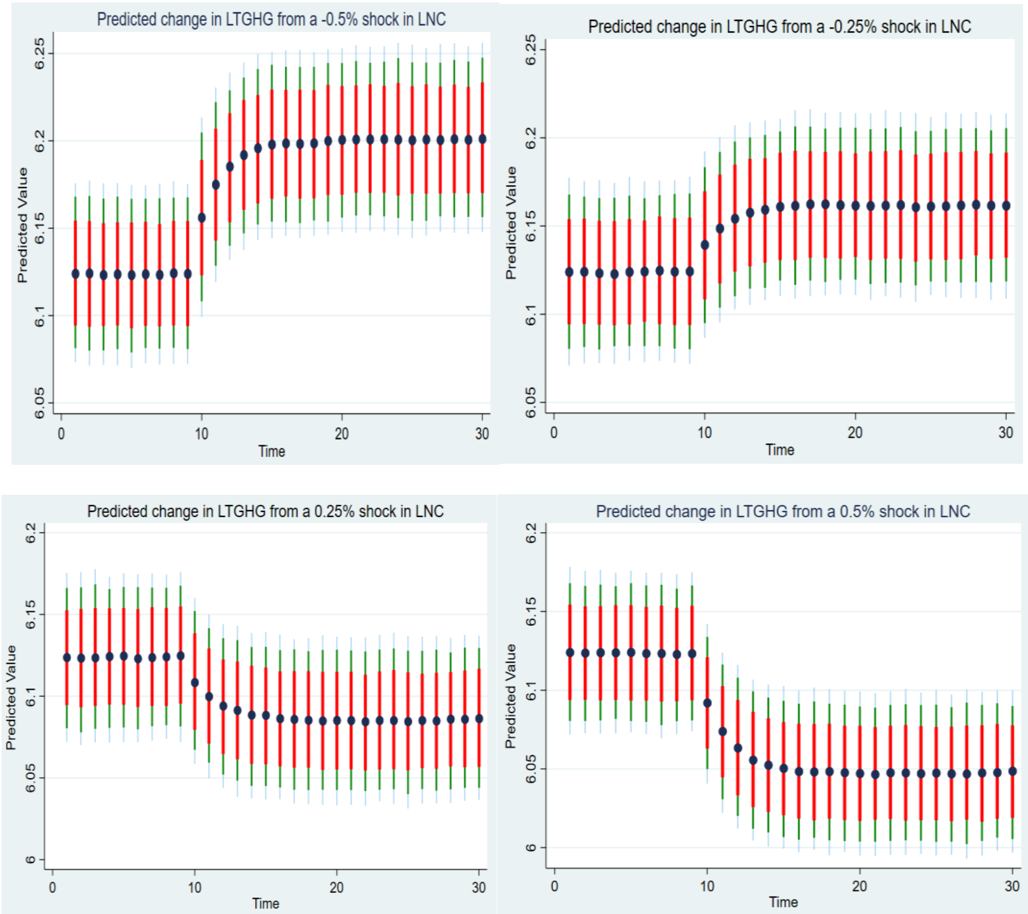

Fig. 7 Dynamic ARDL Simulations of Nuclear Energy Shock on GHG Emissions

Notes: The figure illustrates the predicted change in greenhouse gas emissions (LTGHG) following positive and negative shocks of ±0.25% and ±50% in nuclear energy consumption (LNC), with confidence intervals at 90% and 95%. Positive shocks are associated with emission reductions, whereas negative shocks lead to higher emissions.

The dynamic ARDL simulations reveal pronounced asymmetric effects of nuclear energy consumption shocks on greenhouse gas emissions in France. Specifically, positive shocks (+0.25% and +0.5%) generate a gradual and persistent reduction in emissions, confirming the capacity of nuclear energy to substitute for fossil fuels and thus alleviate carbon intensity in the energy system. In contrast, negative shocks (−0.25% and −0.5%) result in a steady increase in emissions, reflecting the system's reliance on more polluting alternatives when nuclear consumption declines. This asymmetric behavior underscores the dual nature of nuclear energy: while its expansion provides a strategic pathway toward decarbonization, any contraction in its use creates vulnerabilities that jeopardize environmental targets. Accordingly, the findings highlight the necessity of reinforcing nuclear capacity in tandem with scaling up renewable energy investments, in order to achieve a resilient energy mix capable of ensuring both energy security and long-term environmental sustainability.

Conclusion and Recommendations

This study provides robust empirical evidence on the dynamic and asymmetric impacts of nuclear energy consumption on greenhouse gas (GHG) emissions in France over the period 1970–2023, employing both conventional ARDL and Dynamic ARDL (DYNARDL) frameworks. Long-run estimates confirm that nuclear energy significantly mitigates emissions, while DYNARDL simulations reveal asymmetric responses: positive shocks produce sustained emission reductions, whereas negative shocks induce persistent increases. These findings underscore the dual strategic role of nuclear power—as a stabilizing instrument for decarbonization and a potential vulnerability when supply is constrained.
Importantly, the study demonstrates the added value of dynamic simulation techniques for capturing non-linear interactions and system-wide feedbacks that conventional ARDL models may overlook. The results further highlight the synergistic contributions of renewable energy integration, sustainable urbanization, and economic growth in reinforcing a resilient, low-carbon energy system. Short-run adjustments captured by DYNARDL indicate rapid convergence toward equilibrium, emphasizing the capacity of France's energy system to absorb moderate shocks when nuclear energy is effectively deployed.

Policy Recommendations:
1. **Strategic Nuclear Capacity Development:** Expand and modernize nuclear infrastructure to enhance decarbonization potential and ensure energy system stability.
2. **Integrated Renewable Deployment:** Coordinate nuclear expansion with renewable energy investments to diversify the energy mix, improve resilience, and secure sustainable energy supply.
3. **Dynamic, Evidence-Based Risk Management:** Utilize scenario-based dynamic simulations to anticipate asymmetric energy shocks and implement adaptive policy responses.
4. **Sustainable Urban and Economic Planning:** Align urbanization and energy-efficiency policies to maximize emission reductions while supporting economic development.
5. **Forward-Looking Energy Governance:** Establish continuous monitoring and adaptive policy frameworks, informed by dynamic modeling, to mitigate environmental and energy security risks.

In conclusion, France's experience illustrates that nuclear energy, strategically integrated with renewables and guided by evidence-based, dynamic policy frameworks, represents a cornerstone for achieving long-term environmental sustainability, energy security, and a resilient low-carbon economy. This study emphasizes the critical role of dynamic modeling as a policy-planning tool, providing actionable insights for navigating complex decarbonization pathways.

Table 1: Data Sources and Variable Definitions

Symbol	Variable Name	Unit	Source
TGHG	Annual greenhouse gas emissions from fossil fuels and industry - Greenhouse gas emissions	million tonnes	https://ourworldindata.org
NC	Primary energy consumption from nuclear power	terawatt-hours,	https://ourworldindata.org
RC	Primary energy consumption from renewables	terawatt-hours	https://ourworldindata.org
GDP	Gross Domestic Product	(constant 2015 US$)	https://data.worldbank.org
UP	Urban population	Number	https://data.worldbank.org

Table 2 Descriptive statistics

	LTGHG	LNC	LRC	LGDP	LUP
Mean	6.128	6.247	5.383	28.187	17.636
Median	6.130	6.892	5.3146	28.216	17.622
Max.	6.442	7.123	6.010	28.613	17.838
Min.	5.726	2.785	4.968	27.509	17.425
Std.dev.	0.179	1.252	0.244	0.319	0.120
skewness	-0.138	-1.464	0.564	-0.427	0.104
kurtosis	2.576	3.616	2.922	1.962	1.782
Jarque-Bera	0.578	20.151	2.881	4.071	3.434
probability	0.748	0.000	0.236	0.130	0.179

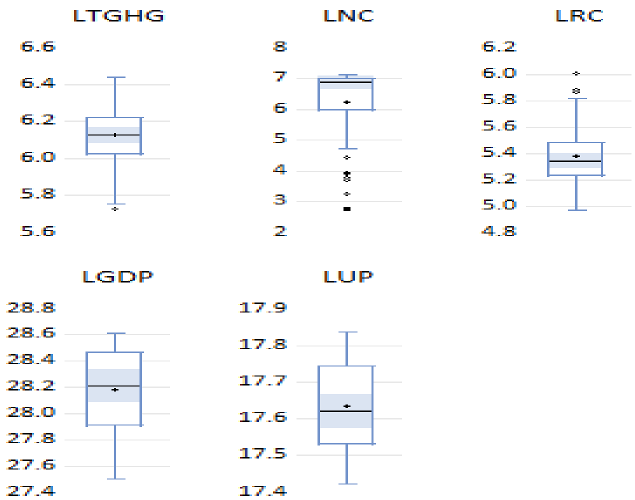

Fig. 2. Box plot

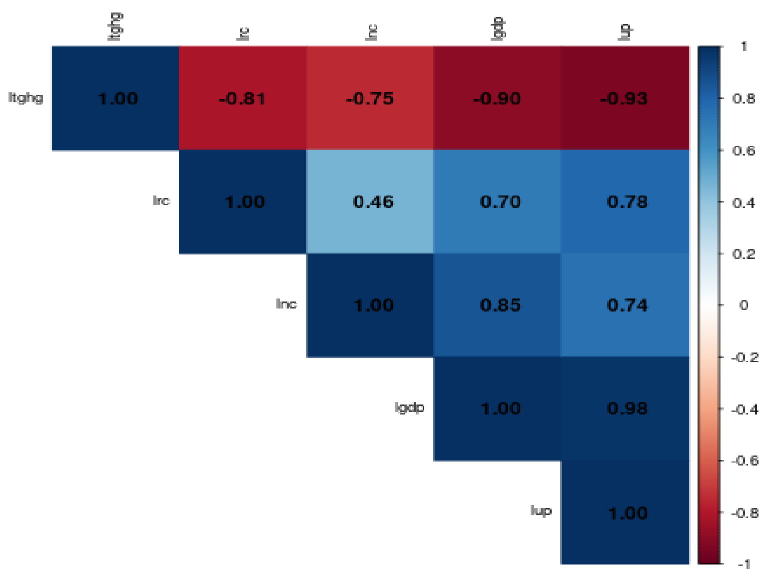

Fig. 3. Correlation graph

Table 3 Results of Unit root tests

Variables	ADF		PP	
	I(0)	I(1)	I(0)	I(1)
LTGHG	0.502	-8.120***	0.784	-8.192***
LNC	-5.597***		-4.478***	
LRC	-1.410	-10.367***	-0.790	-12.097***
LGDP	-3.372***		-4.752***	
LUP	0.923	-3.355***	-0.697	-3.302***

Note: *** represents a 1 % level of significance.

Table 4 Results of the bounds test for cointegration

Test statistic	Value	Significance	I(0)	I(1)
F-statistic	8.130	10%	2.372	3.320
K	4	5%	2.823	3.872
		1%	3.845	5.150

Critical and approximate p-values of Kripfganz and Schneider (2020) (Kripfganz & Schneider, 2020)

Test statistic	value	10%		5%		1%		p-value	
		I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
F	8.130	2.357	3.330	2.798	3.874	3.815	5.115	0.000	0.000
t	-4.684	-2.551	-3.658	-2.885	-4.040	-3.556	-4.794	0.000	0.013

Table 5 The result of long-run and Short-term Coefficients

Long-run		
Variables	Coefficient	Std.Error
LNC	-0.153***	0.024
LRC	-0.173**	0.070
LGDP	1.519***	0.302
LUP	-4.098***	0.693
C	37.483***	4.257
Short-run		
Variables	Coefficient	Std.Error
D(LGDP)	0.907***	0.129
D(LGDP (-1))	-0.698***	0.122
cointEq(-1)	-0.411***	0.055

Table 6 Results of diagnostic tests

Diagnostic tests	Coefficient	p.value	Decision
Jarque-Bera test	0.973	0.614	Normal residual distribution
Ramsey RESET test	1.143	0.290	The model is appropriately specified
Breusch-Godfrey LM test	1.502	0.243	No serial correlation
Breusch-Pagan Godfrey test	0.464	0.854	No heteroscedasticity

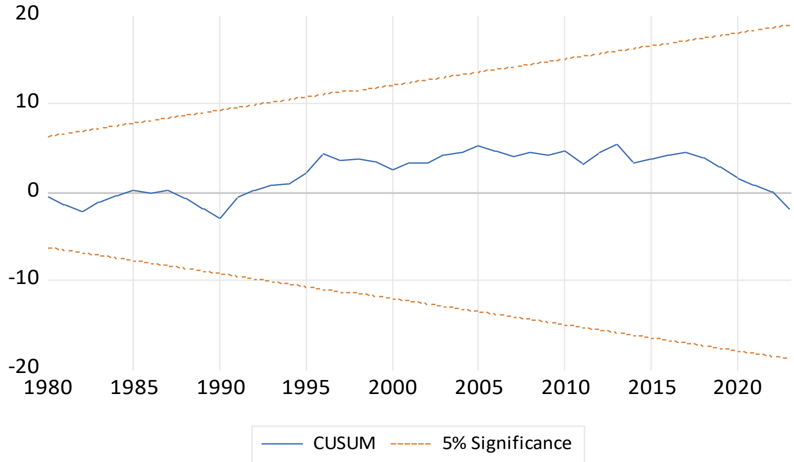

Fig. 4. Result of the CUSUM test.

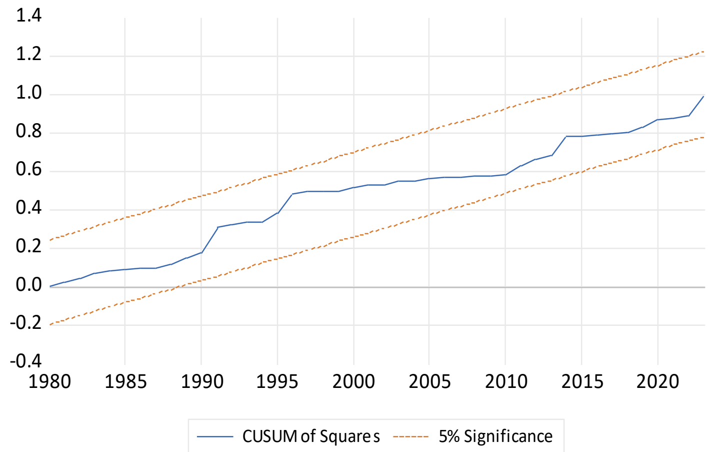

Fig. 5. Result of CUSUMSQ test.

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