

Article

Do Environmental Taxes and Green Electricity Matter for Environmental Quality? Fresh Evidence in France Based on Fourier Methods

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Abstract

The environment has generally served as the foundation and support of human existence and survival over the years through agricultural development, health supply, industrialization, and transportation. This process has resulted in massive environmental degradation. In this postindustrial period, global consensus calls for taking steps to rebalance the degraded environment by planning economic development and social progress while preserving the quality of the environment. In recent years, experts have recognized key factors affecting the quality of the environment where policy is required. The study seeks to explore the impacts of ecological taxes and green electricity on the quality of the environment in France. The work employed Fourier ADL cointegration, novel Fourier autoregressive distributive lag econometric (N-ARDL), and Fourier Toda Yamamoto causality methods. The outcomes of the N-ARDL long-run cointegration estimates imply that both environmental tax and green electricity improve environmental quality in France. Furthermore, the Fourier Toda Yamamoto causality test denotes that both green electricity and environmental tax affect environmental quality in France without a rebound effect. The results recommend that since the “bonus–malus” system of France has suffered a significant rebound effect, the economy could reverse this with environmental taxes focused on reducing pollution. Additionally, the government of France could commit to its current alternative energy plan of 560 TWh of decarbonized electricity yearly from 463 TWh, given the fact that the energy sector is responsible for approximately 11% of total greenhouse gas (GHG) emissions.

Keywords: environmental tax; green electricity; sustainability; Fourier; method; France



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1. Introduction

Environmental quality generally refers to features including air, water purity, noise, open spaces, visual effects of biodiversity, and potential future effects of nature. A number of indicators are used to measure environmental quality quantitatively and qualitatively,

including pollutant concentrations and species health, and by composite indices such as the Environmental Quality Index (EQI), which combine these elements with built-environment characteristics and sociodemographic information. According to scientists, three major environmental issues affecting the global community include global warming, pollution, and habitat loss. They claim that these issues directly relate to human activities in pollution, waste generation, resource extraction, energy use in transportation, and corporate manufacturing processes. Historically, linkages between rising economic activity and the worsening quality of the environment have been found to be explainable through the environmental Kuznets curve [1]. Theoretically, economists claim (under the Pigouvian Framework) that the quality of the environment worsens once the marginal social cost of consuming ecological resources exceeds marginal social benefits [2]. This has recently been explained to relate to increasing worldwide warming—the worst existential global crisis the world has ever known [3,4]. The consequential effects include poor agricultural output, extreme weather conditions, flooding, and poor human health [4]. In recent decades, the worsening state of environmental quality has become a major focus area for policymakers and scientists to find pathways to confronting the associated challenges.

To address this challenge, governments across the world have taken drastic measures through energy productivity measures, regulatory actions, and financial incentives for green energy technology development. One major suggested pathway or factor generally agreed by environmental scientists to have the capability of facilitating drastic improvement in the environmental quality of nations is environmental tax [5,6]. Environmental taxes are policy measures that impose taxes on individual or corporate behaviors that are harmful to the planet's health and halt climate change. These are charges or taxes levied on air pollutants and emissions from industrial production, vehicular use, household waste, and energy use. Environmentalists claim that to incentivize transition to global net zero targets, there should be explicit carbon pricing or other environmentally friendly levers. While green sectors are incentivized, other sectors of human and corporate behaviors (e.g., waste generation, heating, transportation, etc.) are taxed to reduce the effects on humanity. Despite these measures, critics claim, such taxes tend to generate a disproportionate burden on low-income households [7,8].

Another suggested pathway to improving environmental quality and toward sustainable energy transition is green electricity. By definition, green electricity refers to electricity sourced from renewable sources, including wind, solar, and hydro. These sources of energy have been globally found to have lower negative environmental impacts compared to fossil-based fuels such as coal and gas [9]. In the current global decarbonization journey, green electricity serves as the surest path to dealing with climate change and reaching carbon neutrality by 2050. In general, the objectives of electrification remain obvious: economic decarbonization, cleaner air quality guarantee, digitalization of routine activities, and smart public transportation. Notwithstanding its numerous advantages, critics claim its implementation requires a higher upfront cost. Again, the critics claim that the sun and wind continue to remain intermittent globally, besides the required storage capabilities. Further, critics argue that, throughout history, economies have witnessed energy transitions. Unfortunately, the timeline of the 2050 transition is not feasible or realistic. According to critics, American renewable energy consumption since the Paris Agreement has been very low despite policy efforts, and fossil fuel reduction has only reduced from 81.22% (in 2015) to a low 73.08% (in 2020). Critics therefore argue that only a realistic and broad-based policy and environmental factor-spill-over control regulations can ensure the advancement of environmental progress toward the 2050 timeline [10].

For France to achieve its aim of climate neutrality by 2050 compared to 1990 (in line with the EU's plan to become the first climate-neutral continent), the country has committed to

transforming its energy system by curbing fossil fuel consumption, being energy efficient, and relying on green electricity. Over the years and across the EU, France has received high rankings in environmental quality scores. By relying on nuclear energy sources, the economy drastically reduced carbon emissions over the last few decades. The country has had a strong record of protecting terrestrial biomes and marine areas. The economy's energy efficiency policy for the transport sector, found to be the largest energy-consuming sector, is geared towards complete decarbonization by 2050. It supports low-emission transport modes (i.e., seeks modal shift), and offers support for increased penetration of efficient transportation modes. Aimed towards realizing these objectives, the economy of France offers key measures, including an ecological bonus–malus scheme for new and optimized cars, sustainable mobility allowances, and implements the Electrotechnical Certification Schemes (ECS), such as carpooling or the purchase of less energy-intensive vehicles, in line with European directives on mandatory standards for transport sector emissions. However, temperature rises in France have been higher than usual, underscoring the country's susceptibility to climate change.

Furthermore, according to experts, environmental health concerns have not received much attention from policymakers. The agricultural sector's powerful political clout has hindered species preservation in the last ten years. Despite its strong international commitments, France is not on course to reach its net-zero emissions target by 2050, despite having played a significant role in the negotiations that resulted in the 2015 Paris Agreement. The recent Zero Carbon Commission (ZCC) estimates indicate that carbon pricing in France could increase to GBP 27 billion per year by 2030. In 2022, the country was the largest net power importer because of an unstable nuclear output. Further, environmental researchers have found that, since 2022, France has stayed behind schedule on net-zero targets. The European Commission has warned France for failing to designate zones vulnerable to pollution by nitrates. Finally, water quality investigation in France continues to indicate that water monitoring standards are not properly carried out.

Based on these findings, a dedicated study on France will give clarity to the environmental situation of the economy and add to the literature on the topic. A focused study on France will provide a real-world case study for major economies actively implementing policies to decouple economic growth from environmental degradation. It offers valuable lessons for other nations on how to design and implement effective environmental policies. As part of its tax policy, France is promoting the use of green electricity. Despite historically relying on nuclear power, the country has increased its investment in renewable energy sources such as wind and solar [11]. As part of its strategy to achieve carbon neutrality by 2050, this transition is a crucial element. An in-depth study of France's approach to green electricity provides valuable insight into how a nation with a mature and centralized energy system can integrate variable renewable energy sources. As part of this process, it is necessary to examine the technological challenges, the policy frameworks that encourage investment, as well as the social and economic consequences of shifting away from traditional energy sources.

As a leader in using environmental taxes to influence behavior and fund ecological initiatives, France has set the standard. In 2014, the country introduced a carbon tax (Contribution Climat-Énergie). As a result of placing a price on carbon emissions, France intends to encourage individuals as well as industries to reduce their fossil fuel consumption. The study of the effectiveness of this tax provides important information regarding how fiscal policy can be used for environmental protection. To understand the economic impacts, the acceptance of such measures by the public, and their overall success in reducing greenhouse gas emissions, researchers and policymakers look to France.

Due to the paucity of research on the impacts of green power and ecological taxes on environmental quality, this paper uses innovative Fourier autoregressive distributive lag econometric techniques to close the gap and clarify pertinent points. The Pigouvian tax [12]

and the cap-and-trade ecological tax theory serve as the study's driving forces [13]. The work progresses as follows: the next section is a review of relevant literature to develop conceptual models and construct assumptions for practical assessment. Following the literature review are the methodology and empirical findings. The last section concludes the study and offers policy suggestions.

2. Literature Review

Ecological quality is defined by the role it plays for mankind and as a sink for dissipating harmful air, water, and solid pollutants or absorbing wastes. Human actions that cause a reversal in this role of improving environmental quality pose an existential risk to humanity, which, according to experts, requires a policy response. In effect, a policy response could concern the factors that promote economic development, with limited abatement action resulting from environmental pollution. Historically, the theoretical literature has focused on the Environmental Kuznets Curve (EKC), which explains an inverted-U shape curve of pollution indicators on income per capita. This has been explained as being due to variations in the composition of output, technological progress, and rising demand for ecological quality as income grows [14,15]. Notwithstanding, most authors are inclined to agree that the nexus between ecological quality and economic growth can be explained by a myriad of factors, involving those that create and those that reduce environmental quality destruction.

This review suggests an empirical econometric model of linkages among numerous factors and environmental quality. Specifically, the study seeks to develop a model that helps to directly explain the linkage between economic growth, primary energy use, green electricity, environmental tax, and environmental quality. To realize this objective, this section examines the pertinent research to gain an understanding by developing a conceptual background and setting up the work for empirical analysis.

2.1. The Environmental Tax and CO₂ Emissions Nexus

Ecological tax refers to a tariff on actions that have a positive effect on environmental sustainability. In effect, environmental taxes are policy instruments to protect the quality of the environment. The authors of [5] investigated environmental taxes and found them to help decrease carbon emissions by forcing a reduction in demand for fossil fuels or a reduction in carbon emissions. Globally, economies use environmental taxes to realize delivery targets of the Kyoto Protocol and the Paris Climate Agreement. In theory, ecological taxes are anchored on improving social welfare [16,17]. This is because experts have found that environmental degradation is problematic due to damage to both society and the economy. Given the divergent classification of private and social costs of pollution, the authors of [12] emphasized that pollution tax balances social marginal damage and the private costs of actions. Critics of the theory, however, argue that there is no global optimal efficiency of energy use or carbon taxes, subsidies, and voluntary transfers. The critics further argue that environmental taxes are inclined to be regressive against poorer households and compel them to use inexpensive and less energy-effective appliances [18]. Despite this criticism, proponents claim the regressive potential can easily be controlled by numerous policy tools, ensuring that environmental goals are met without placing an undue burden on the most vulnerable populations, for example, by using revenue generated from the taxes to offset their impact on low-income households, such as improving and expanding public transportation options to provide affordable alternatives for those most affected by higher fuel prices [12].

Likewise, environmental taxes frequently result in double taxing on both intermediate inputs and ultimate products due to their small tax base [19]. As an alternate theory, other scientists recommend a cap-and-trade system because they claim carbon taxes place a cost on CO₂ emissions and permit markets to freely determine levels of pollution. According to them,

cap-and-trade systems ensure pollution limits and offer corporations or individuals regulated rights to pollute [13]. Critics, however, have cited three arguments in support of carbon taxes as opposed to cap-and-trade schemes. First, a cap-and-trade system makes it impossible for businesses to plan for long-term, capital-intensive projects because it causes price fluctuations in response to shifting market conditions. Secondly, it is administratively complicated and necessitates many systems for tracking, auctions, and the creation of uniform regulations to prevent fraud and misuse. Finally, it has the potential to be counterproductive due to policy interactions or interference in corporate production processes.

Ecological taxes have been shown to lower CO₂ in a number of empirical studies examining their impact on pollution [20,21]. In their studies in China, Ref. [22] found that ecological taxes greatly lower carbon emissions, play a key role in promoting the advancement of renewable energy technology and contribute to a reduction in energy consumption. When Ref. [23] looked into EU policies for mitigating carbon emissions, they discovered that environmental levies were a very successful strategy for lowering carbon emissions in all member economies. According to a related study by [24] on the effect of ecological taxes on international competitiveness in European nations, environmental taxes are highly successful in fostering economic well-being and market competitiveness. But according to other experts' research, environmental fees do not really help cut carbon emissions. The authors of [25–27] asserted, for instance, that ecological taxes can only preserve ecological quality if energy and ecological technology investments are given priority, while in [28], they examined the long-term impacts of environmental levies on energy consumption using data from 25 European economies between 1995 and 2005. The results showed that environmental levies had minimal impact on the energy use of the countries under study.

2.2. Green Electricity and CO₂ Emissions' Nexus

Energy is the convertible currency of technology, but problems with energy production and use are related both to worldwide warming and other ecological concerns, including air pollution, acid precipitation, ozone depletion, forest destruction, and the emission of radioactive substances. Experts and policymakers claim these environmental issues must be considered simultaneously to ensure the future survival of humanity. In theory, productive and efficient energy use ensures the protection of the quality of the environment. This is achieved by reducing environmental pollution and carbon dioxide emissions [29]. Several scientists argue that to achieve total benefits from the eco-environment, energy generation needs to shift from traditional fossil fuels to green or renewable energy sources [30–34]. They claim the adoption of renewable energy technologies help to produce marketable energy through the conversion of natural phenomena into useful energy forms [29,35–38]. Notwithstanding, critics argue that despite the optimism of the green electricity crusaders for years, progress in using clean energy remains limited, and a large percentage of electricity and fuel use is still generated by dirty energy sources, such as coal, oil, and natural gas.

Empirically, environmental scientists and economists have indicated that energy use remains the leading contributor to rising CO₂ levels and the destruction of ecological quality [39–41]. These findings have been the result of testing growth, conservation, feedback, and neutrality hypotheses [42]. Several other studies have indicated a causal nexus between economic development and CO₂ emissions using numerous econometric techniques (e.g., [43]). These scholars claim that if appropriate investments are made in green electricity or renewable energy for electricity generation, it is possible for the global economy to become energy-independent in the long run [44].

2.3. Economic Growth and Environmental Quality Nexus

Across the world, academic and policy interest in the ecological effects of economic growth has been concerning. This interest has increased because of the publication on linkages between economic growth and the deteriorating environment in 1987. In the 1990s, EKC was used to explain this issue. This theory argues for a trade-off between growth and quality of the environment and challenges conservative economic theory, which states that economic development is a prerequisite for ecological sustainability [14,45]. Empirically, this theory has been confirmed by [46], who investigated the nexus among CO₂, energy consumption, and growth in selected BRIC nations from 1971 to 2005, and Russia from 1990 to 2005. Other studies that confirm the EKC hypothesis include [47] in Qatar and [48] in Azerbaijan between 1992 and 2013. Other studies fail to validate the EKC hypothesis [49–51].

2.4. Primary Energy Consumption

Globally, the use of energy is essential to the development of the economy and society, as well as to improvement in the quality of life. Energy is presently produced and consumed in ways that cannot be sustained if technology remains constant and if overall quantities remain constant. Energy use for production, especially for transportation, has been to generate CO₂. Researchers have found that the most common GHG is CO₂, and two of the largest global sources are electricity, heat, and transportation [52]. In order to control GHG emissions in the country, efficiency in energy production, transmission, distribution, and consumption will become increasingly important. In the case of France, in order to realize the objectives of this study, primary energy consumption is controlled to assess the polluting effect of green electricity and environmental tax. Primary energy is defined as energy sourced from nature, not already engineered before by a conversion process. It is energy (both renewable and non-renewable) contained in raw fuels and other energy forms, including waste. Primary energy use is a measure of the total energy use of a nation.

Scientists claim the relationship between economic activity, primary energy use, and CO₂ emissions is not always linear or symmetrical [53,54]. A shock that causes a 10% drop in GDP may not lead to a proportionate 10% drop in emissions if the composition of energy use shifts towards dirtier, cheaper sources, or if policy priorities change during a recession. The ultimate effect depends on the specific characteristics of the economy, including its energy mix, level of development, and government policy responses. A positive economic shock (e.g., an economic boom or a sudden increase in demand) typically leads to a direct increase in primary energy use and, consequently, an increase in CO₂ emissions. Economic growth drives higher industrial output, more transportation of goods, and greater consumer spending on energy-intensive products and services. All these activities require more energy, much of which is still derived from fossil fuels. A negative economic shock (e.g., a recession or financial crisis) usually leads to a decrease in primary energy use, which in turn can decrease CO₂ emissions. However, there are theoretical arguments for why emissions could increase or remain unchanged.

2.5. Gaps in Research

Based on these review actions, it is clear that hypothetically, both green electricity and environmental tax can improve or cause destruction to environmental quality, depending on various factors in the theory of practice. Similarly, primary energy consumption and economic growth could both improve or cause destruction to environmental quality, depending on various issues in the theory of practice. It is therefore assumed that these will be the case for France; unfortunately, to the best of our understanding, while studies exist on green electricity [55]; environmental tax [56]; primary energy consumption [57]; and

economic growth [58], no such empirical study has been considered in the literature that combines all four variables to assess environmental quality concerns.

3. Methodology

The paper seeks to investigate the effects of environmental taxes and green electricity on the quality of the environment in France from 1995 to 2020. This study employed a quadratic approach to transform time series data from annual to quarterly frequencies. Economic growth and primary energy use are employed as controlled variables. To realize the objectives of the study, data were collected on (i) carbon dioxide emissions as a proxy variable for quality of the environment (CO_2); data were sourced from World Bank (ii) gross domestic product (GDP) is used as a proxy for economic growth; data were sourced from World Bank (iii) renewable electricity, % total electricity generation is used as a proxy for green electricity (GELEC); data were sourced from Energy Institute—Statistical Review of World Energy; (iv) environmentally related taxes, % GDP is used as a proxy for environmental tax (ETAX); data were sourced from OECD; and (v) primary energy consumption (LPEC); data were sourced from our world in data. These data were collected based on both theoretical and empirical understandings from the literature review [59]. Data were reconciled using Eviews 12 statistical software, which has built-in functions to handle data reconciliation, including both aggregation and interpolation/disaggregation. To avoid scaling limitations, some data transformation into natural logarithm forms became necessary [60]. It must be noted that it is not necessary to log all variables because not all variables require transformation [61]. The analysis flow chart is reported in Figure 1.

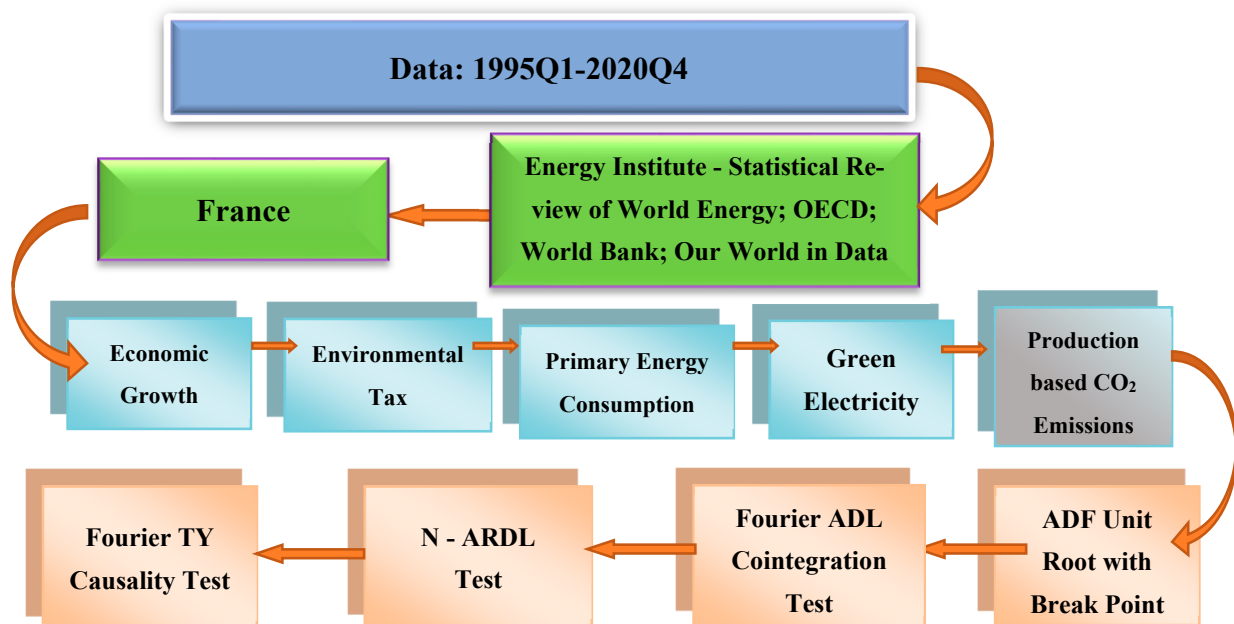


Figure 1. Analysis flowchart.

3.1. Theoretical Motivations

In theory, productive and efficient energy utilization promotes the quality of the environment by reducing pollution and CO_2 [16]. Such a reduction in CO_2 emissions will improve the quality of the environment and prevent the adverse effects of global warming. To achieve the benefits of the eco-environment, sourcing energy needs to shift from conventional fossil fuels to green or renewable energy sources. Currently, given the rising global concerns about fossil fuel energy use for economic activities and the deteriorating quality of the environment, the United Nations is leading a crusade for

successful alternative energy transformation with ambitious targets. The environmental tax has historically been suggested as a major policy pathway.

Despite debates, Ref. [12] argued on the divergence between individual and social prices for units of pollution generated. Based on this, Ref. [12] argued the need to tax pollution to ensure efficient market outcomes. Additionally, to deal with the ills of climate change and reach carbon neutrality by 2050, environmental scientists claim global decarbonization using green electricity provides the surest path to net zero transition. To estimate the relationships between economic growth, primary energy consumption, green electricity, environmental tax, and environmental quality, this paper is motivated by the Stokey framework establishing environmental degradation and abatement impacts of regulatory action [62]. This framework explains the relationship between rapidly increasing fuel consumption, economic growth, and environmental quality. It also explains how environmental tax deals with global emission variations, and can facilitate innovations in energy use. The paper is also motivated by the EKC hypothesis and the effect of technological progress on the growth rate of output and environmental quality over time. Accordingly, to realize our objectives, the empirical model for the work is as follows:

$$CO_2 = f(GDP, GELEC, ETAX, PEC) \quad (1)$$

where CO_2 is carbon dioxide emissions (as a proxy variable for the quality of the environment in France), GDP is gross domestic product (as a proxy variable for economic growth), PEC is primary energy use; ETAX is environmental tax, and GELEC is green electricity.

Next, by logging CO_2 , LGDP and PEC variables, the model is indicated as:

$$LCO_{2t} = LGDP_t + GELEC_t + ETAX_t + LPEC_t + e_t \quad (2)$$

where LCO_2 is natural logarithm of carbon dioxide emissions (as a proxy variable for quality of the environment in France); LGDP is natural logarithm of gross domestic product (as a proxy variable for economic growth); and LPEC is natural logarithm of primary energy use; ETAX is environmental tax, GELEC is green electricity, and e_t is the error term.

3.2. Pre-Estimation Approaches

(i) BDS tests

In econometric assessments, structural breaks historically have been disregarded. However, experts have observed that such disregard causes biases in eventual unit root estimates. To determine the integration order of variables, the BDS test is performed to identify possible stochastic hidden and nonlinear patterns. Additionally, determining BDS information can help identify model misspecification and judgmental errors. The BDS model is determined by:

$$BDS_{mT}(\varepsilon) = T^{1/2} [C_{m,T}(\varepsilon) - C_{1,T}(\varepsilon)m] / \delta_{mT}(\varepsilon) \quad (3)$$

Here, T refers to sample size; ε is the proximity parameter, which is randomly adopted; and $\delta_{mT}(\varepsilon)$ refers to the standard deviation of the varying numerator, given the dimension “m” [63].

(ii) ADF unit root with breakpoint

The study then uses Augmented Dickey-Fuller (ADF) unit root tests with breakpoints to verify the integration order of serried variables following descriptive statistical evaluations. In econometrics, models cannot be tested for cointegration using the standard cointegration techniques when variables are integrated to differing degrees. In spite of the integration order, this study uses the new ADF unit root tests with breakpoints, which

offer more accurate and trustworthy data for cointegration assessment. The model used to estimate the unit roots for ADF with breaks is:

$$x_t = \mu + \rho x_{t-1} + e_t \quad (4)$$

where, variables are denoted by x_t ; μ denotes the constant; e_t is the error term. The model $\Delta x_t = \mu + e_t$ if differenced; in this case $\Delta = (1 - B)$; ρ is the parameter slopes for all variables lagged, becoming 1 in the presence of unit root. ADF unit root with breaks is:

$$x_t = \mu + \beta_t \delta DU_t + \theta D(T_B)_t + e_t \quad (5)$$

The error correction forms re-specification and augmentation factor, ADF with breaks equation, is estimated as:

$$\Delta x_t = \mu + \beta_t + \gamma_1 \sin\left(\frac{2\pi kt}{N}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{N}\right) + (\rho - 1)x_{t-1} + \sum_{i=1}^p c_i \Delta x_{t-i} + e_t \quad (6)$$

' c ' is a slope parameter of augmented parts; p is lag; k is Fourier regularity; T_B denotes the date of the structural break date; and λ . Is a break fraction.

(iii) Fourier ADL cointegration test

In economics analysis, serried data are found subject to several varied structural breaks, making the estimation models generate misspecification issues and incorrect conclusions. Based on the outcomes of the unit root test, the autoregressive distributive lag (ADL) cointegration test which can deal with nonlinear breaks approximated by a Fourier function is employed. The approach can capture a smooth, gradual, and unknown number of structural changes without power loss by circumventing and adding dummy variables during model testing [64,65]. The model is as follows:

$$d(t) = \sum_{k=1}^n a_k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^n b_k \cos\left(\frac{2\pi kt}{T}\right) \quad (7)$$

' n ' is frequency; $\pi = 3.14$, ' k ' is special frequencies used, ' t ' is trend, and ' T ' is sample size. A single frequency value is suggested [66] as in the equation. Several experts have used frequency values at the minimum sum of squared residuals [65–68].

$$d(t) = \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) \quad (8)$$

(iv) Fourier nonlinear ARDL long-run equilibrium analysis

For many years in econometric analysis, traditional ARDL cointegration has historically been unable to identify and deal with hidden long-term nonlinear interactions among variables [69]. Fortunately, in recent years, the Fourier nonlinear ARDL (N-ARDL) estimator has been applied by experts to estimate long-run equilibrium interactions accurately in the presence of structural breaks, both in time and structure [68,70]. While conventional methods like ARMA or ARIMA models focus on relationships between past and present values in the time domain, Fourier-based analysis shifts the focus to the frequency domain, decomposing the signal into its underlying sine and cosine waves.

One major advantage of the N-ARDL approach is to control heteroscedasticity and serial correlation in time-serried data. The N-ARDL method is generally praised by scientists for its ability to apply despite the integration of factors, i.e., level (I(0)), differenced (I(1)), or mixed regressors. Further, the method can explain response variations in the dependent factor, Y_t , (increases (+) and decreases (−) resulting from unit changes in independent variables, X_t . This is modeled as:

$$Y_t = \beta_0 + \beta_1 X_t + \mu_t \quad (9)$$

Y_t is the dependent variable; X_t is the determinant regressor; and β_1 is the variation of Y_t as a direct result of unit variations in X_{it} .

The approach uses a two-step model to account for structural shifts [71]. The partial sums of $X + t$ or partial sums of $X - t$ are reformulated for a long-run asymmetric model and specified as:

$$Y_t = \beta_0 + \beta_1^+ X_t^+ + \beta_1^- X_t^- + \mu_t \quad (10)$$

The N-FARDL model is:

$$\begin{aligned} \Delta LCO_{2t} = & \beta_0 + \sum_{i=1}^{\rho-1} \beta_1 LCO_{2t-1}^+ + \sum_{i=1}^{\rho-1} \beta_1 LCO_{2t-1}^- + \sum_{i=1}^{\rho-1} \beta_2 LGDP_{t-1}^+ + \sum_{i=1}^{\rho-1} \beta_2 LGDP_{t-1}^- + \sum_{i=1}^{\rho-1} \beta_3 LPEC_{t-1}^+ \\ & + \sum_{i=1}^{\rho-1} \beta_3 LPEC_{t-1}^- + \sum_{i=1}^{\rho-1} \beta_4 ETAX_{t-1}^+ + \sum_{i=1}^{\rho-1} \beta_4 ETAX_{t-1}^- + \sum_{i=1}^{\rho-1} \beta_5 GELEC_{t-1}^+ \\ & + \sum_{i=1}^{\rho-1} \beta_5 GELEC_{t-1}^- + \varphi LCO_{2t-1} + \varphi_1^+ LGDP_{t-1} + \varphi_2^- LGDP_{t-1} + \varphi_1^+ LPEC_{t-1} + \varphi_2^- LPEC_{t-1} \\ & + \varphi_1^+ ETAX_{t-1} + \varphi_2^- ETAX_{t-1} + \varphi_1^+ GELEC_{t-1} + \varphi_2^- GELEC_{t-1} + \mu_t \end{aligned} \quad (11)$$

$\Delta Y_t = \beta_0 + \sum_{i=1}^p \beta_1 \Delta y_{t-1} + \sum_{i=0}^q \beta_2 \Delta X_{t-i}^+ + \sum_{i=0}^q \beta_3 \Delta X_{t-i}^- + \sum_{i=0}^q \beta_4 \Delta X_{t-i}^-$ signify short-run and $\rho y_{t-1} + \varphi_1^+ X_{t-1}^+ + \varphi_2^- X_{t-1}^- + \dots$, indicates long-run valuation. Similarly, X_t^+ and X_t^- are partial sums of POS (+) and NEG (−) variations in X_t . N-ARDL frameworks assess the long-run connection between X^+ , X^- regressors, and Y [69]. Long-run asymmetric effects of X_1 on Y are calculated as $L_{M1+} = \frac{-\varphi_1^+}{\rho}$ and $L_{M1-} = \frac{-\varphi_1^-}{\rho}$; short-run asymmetric effects of X_1 on Y . If symmetry is rejected, the conclusion is that the effect of X on Y is asymmetric. Figure 2 shows the nonlinear framework of the estimated model.

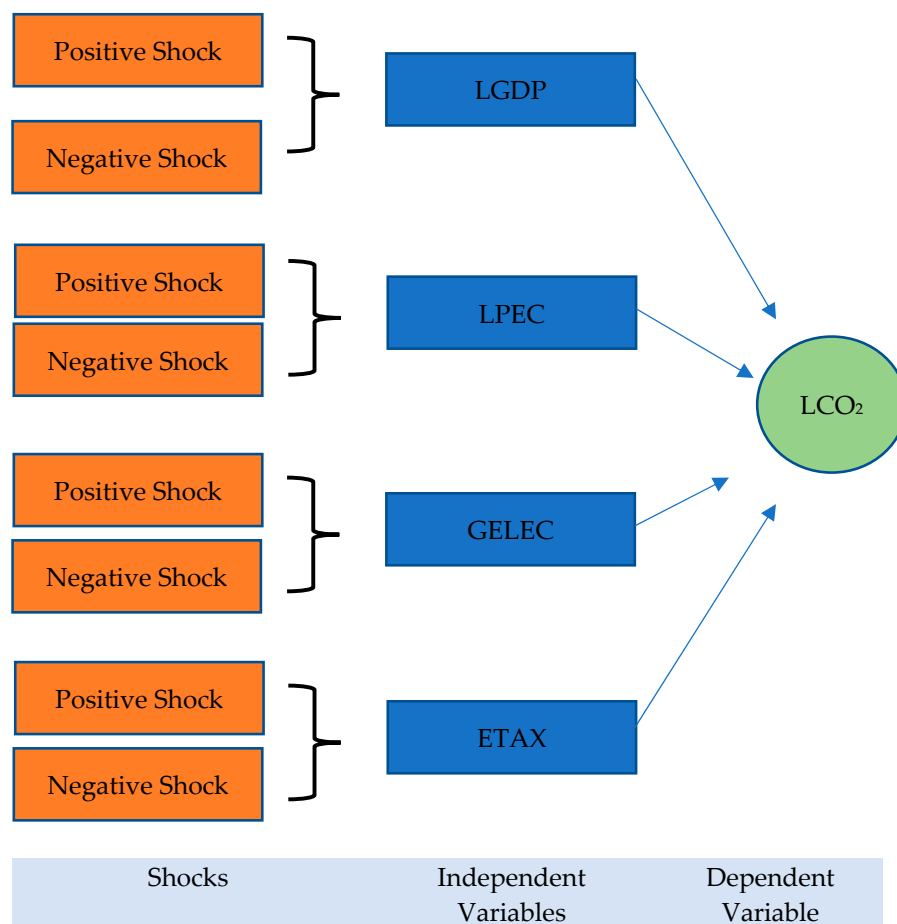


Figure 2. Non-linear framework.

Finally, the work performs the Fourier Toda Yamamoto causality test to validate the outcomes of the Fourier ARDL estimates.

4. Empirical Findings

The work seeks to explore the impacts of ecological taxes and green electricity on the quality of the environment in France. Other variables employed in the model, such as economic output and primary energy consumption, were used as controlled variables (Table 1).

Table 1. Descriptive statistics.

Codes	LCO ₂	LGDP	GELEC	ETAX	LPEC
Variables	Production-Based CO ₂ Emissions	GDP (Constant 2015 USD) Per Capita	Renewable Electricity, % Total Electricity Generation	Environmentally Related Taxes, % GDP	Primary Energy Consumption
Mean	2.527998	12.34732	14.50692	2.355769	3.468990
Median	2.541802	12.36056	13.68828	2.352500	3.471754
Maximum	2.573643	12.42159	25.76187	2.567813	3.501445
Minimum	2.388085	12.24683	9.764687	2.135938	3.365992
Std. Dev.	0.040137	0.047457	3.229695	0.131272	0.026311
Skewness	−1.036139	−0.649484	1.054900	0.037777	−1.084429
Kurtosis	3.666659	2.438219	4.038433	1.692861	4.724851
Jarque–Bera	20.53468	8.679293	23.96159	7.428726	33.27590
Probability	0.000035	0.013041	0.000006	0.024371	0.000000

Per the findings of the descriptive analysis (Table 1), no outliers are detected in the dataset. Similarly, the results reveal that factors are normally distributed, suggesting that further analysis could be performed. To proceed, the paper checks the linearity or non-linearity of the serried variables using the BDS approach [72] towards detecting possible hidden nonlinearities and to check if the model is not specified correctly or contains judgmental errors.

Per the outcomes of the BDS estimates (Table 2), it is clear that the null hypothesis is rejected, indicating hidden nonlinear patterns could be found, because all variables exhibit significant dimensional critical values that are higher than their corresponding BDS estimates. This outcome paves way for authors to conduct variable stationary tests using non-linear-based econometric methods.

Table 2. BDS test.

Variables	LCO ₂	LGDP	GELEC	ETAX	LPEC
Dimension	BDS Stat.	BDS Stat.	BDS Stat.	BDS Stat.	BDS Stat.
2	0.176267	0.207265	0.168709	0.180382	0.172110
3	0.288204	0.353350	0.273447	0.300169	0.278263
4	0.364665	0.454811	0.338027	0.375532	0.343607
5	0.418508	0.524817	0.377532	0.418864	0.388732
6	0.457172	0.573683	0.404864	0.442655	0.419435

The results of the unit root test, as shown in Table 3, report that the LCO₂, LGDP, GELEC, ETAX, and LPEC variables are integrated at order one (i.e., I(1)) with breakpoint at 1997Q1, 2018Q4; 1998Q4; 1998Q1 and 2017Q. This finding demonstrates that factors are integrated at first difference. The existence of structural breaks is validated because, environmentally, 1998 saw a period of policy maturation after the 1992 law that taxed landfilling; France was fully focused on Maastricht Treaty convergence criteria to join the

European Monetary Union (EMU) on 1 January 1999. This period also saw ongoing efforts to curb pollution from industrial facilities and urban wastewater treatment plants, with a notable reduction in phosphate levels in rivers. Additionally, the structural break is validated by the “Gilets Jaunes” protests in 2018, which affected fuel prices. Specifically, the movement argued that a disproportionate burden of taxation falls on the working and middle classes in France, particularly in rural and peri-urban areas. Among other things, protesters called for lower fuel taxes, the reinstatement of the solidarity tax on wealth, and an increase in the minimum wage. Additionally, the year 2017 saw a major policy change on climate change financing and international cooperation. This resulted in a reduction of the share of nuclear energy in the country’s energy mix, and further domestic plans to ban all future oil and gas exploration licenses, which critics claimed was largely a symbolic step since France had very few domestic fossils fuel reserves during the period.

Table 3. ADF unit root test with break point.

Variables	ADF	Break Point
LCO ₂	−2.730	2018Q4
LGDP	−3.130	2010Q2
GELEC	−2.505	2011Q2
ETAX	−3.978	2005Q1
LPEC	−2.851	2018Q4
LCO ₂	−5.261 **	1997Q1
LGDP	−6.086 ***	2018Q4
GELEC	−5.888 ***	1998Q4
ETAX	−5.499 **	1998Q1
LPEC	−5.804 ***	2017Q1

Note: At the 5% and 1% levels, respectively, the symbols ** and *** indicate statistical significance.

Given these outcomes, the paper checks the cointegration properties of variables using the Fourier ADL cointegration estimator. By testing for cointegration, it is possible to determine how ETAX, LGDP, LPEC, and GELEC jointly affect LCO₂ in the case of France.

The results of N-ARDL bounds and Fourier ADL cointegration show that there are long-term equilibrium relations between the independent and dependent variables (see Tables 4 and 5).

Table 4. Fourier ADL cointegration analysis.

Model	Test Statistic	Frequency	Min AIC
LCO ₂ = f(LGDP, GELEC, ETAX, LPEC)	−5.707	0.200	−8.081

Table 5. N-ARDL bounds and long-run results.

N-ARDL Bounds Results				
F-statistics		7.076		
K		8		
N-ARDL Long-Run Results				
Variables	Coefficient	Std. Error	t-Statistic	Prob.
GELEC_POS	−0.005098	0.001014	−5.026512	0.0000
GELEC_NEG	0.000097	0.000997	0.098216	0.9220
LGDP_POS	−0.484297	0.215801	−2.244184	0.0280
LGDP_NEG	−0.234380	0.277286	−0.845262	0.4008
ETAX_POS	−0.043468	0.019489	−2.230330	0.0289
ETAX_NEG	0.064726	0.019684	3.288184	0.0016
LPEC_POS	0.882688	0.205284	4.299834	0.0001
LPEC_NEG	1.341291	0.197400	6.794798	0.0000

4.1. Interpretation of Outcomes and Discussions

The long-run non-linear ARDL (N-ARDL) estimates indicate that variables have varied coefficients with significant statistical values depending on the economic shock period. First, the results of the N-ARDL long-run cointegration estimates (Table 5) show that, for LGDP, there is a long-term positive and negative non-linear causal effect on LCO₂, with both positive and negative coefficients (−0.484297 and −0.234380, respectively) that are significant.

First, as they move in opposite directions in France, a 1% increase in LGDP causes LCO₂ to fall by roughly 48.42% during its positive shock periods, while a 1% decrease in LGDP causes a surprise rise in LCO₂ by −0.234380% during its negative shock periods, all other things being equal. A negative GDP shock can disrupt the long-term trend of decoupling economic growth from emissions. In many developed countries, CO₂ emissions have been falling even as GDP has risen, thanks to improvements in energy efficiency, a shift to cleaner energy sources, and the transition from heavy industry to a service-based economy. For instance, a negative economic shock can interrupt this progress. When a recession hits, companies may cut back on investment in new, more efficient, and cleaner technologies. They may also defer or cancel plans to upgrade old, polluting equipment. This pause in “green” investment can halt the downward trajectory of emissions, and as the economy recovers, the use of older, less-efficient technology could lead to a sudden surge in emissions. Similarly, a recession reduces tax revenue for governments. This can lead to cuts in public spending, including funding for green infrastructure, research into clean technology, and environmental monitoring and enforcement. Additionally, the EKC hypothesis claims, at a certain point (high GDP), as the economy becomes wealthier, it can afford to invest in cleaner technologies and prioritize environmental protection, leading to a decline in pollution; this makes it correct to claim that a negative GDP shock could push a country back down the “cleaner” side of the curve, potentially causing a temporary increase in emissions as a result of a decline in environmental investment and focus. While this is a broad theoretical framework, it helps explain why a drop in GDP would not automatically lead to an environmental improvement.

In contrast to negative shock periods, positive shock periods for LGDP contribute to a decrease in carbon emissions in France. This outcome corroborates the hypothesis established for this study on the effect of LGDP on LCO₂ in the case of France. It is noteworthy to recognize that the decomposition factor power of the N-ARDL estimator helps to establish the need to implement policies for the decoupling of LGDP from LCO₂ in France during shock periods. This result supports the recent study by [73] in the case of China. Theoretically, rising economic growth simultaneously results in more demand for energy and material resources for production, producing a worsening quality of the environment. This is the claim of the EKC framework, which underlines that the first stage of economic expansion results in environmental degradation until environmental regulations and technological advancements intervene to rectify the anomaly. With reduced LCO₂ during positive economic shocks in France, the outcome suggests the economy has reached the EKC peak, with high levels of technological and innovation progress.

In sum, economic growth had a mixed effect on the quality of the environment in France, following a pattern often described by the Environmental Kuznets Curve (EKC). It must also be noted that France, as a high-income economy, had reached the declining curve of the EKC framework for many traditional pollutants during the period under study. Its economic growth was more closely associated with policies aimed at improving environmental quality. In practical terms, the mixed effect of economic growth on environmental quality for the case of France indicated that the economy of France needed to ensure that economic policies and environmental goals were aligned. In this case, a combination of

carbon taxes, subsidies for green investment, and regulations targeted towards steering the economy were geared towards a truly sustainable path. For corporate strategy, managers could ensure regulatory policies on production equally influenced consumption patterns towards reducing waste generation and avoided a “race to the bottom” on corporate environmental footprint.

Second, the N-ARDL long-run cointegration estimates (Table 5) show a positive and negative non-linear causal effect on LCO_2 for GELEC with coefficients -0.005098 and 0.000097 at positive and negative shocks, respectively. These imply that a 1% increase in GELEC causes a decrease in LCO_2 by approximately 0.005098% at positive shock periods, while a 1% decrease in GELEC during negative shock periods leads to a reduction in LCO_2 by 0.000097% as they move in a similar direction. This finding corroborates the hypothesis established on GELEC on LCO_2 for the case of France. Theoretically, investments in green electricity lead to a reduction in CO_2 . It is important to recognize that France is committed to transforming its energy system by curbing fossil fuel consumption, being energy efficient, and relying on green electricity with huge budgetary allocations. It is also worth noting that for a robust transition to net zero to occur, huge investments in green innovation projects matter. For the case of France, the outcomes indicate that periods of no or reduced investments in green energy technologies result in rising carbon emissions. By aligning with the Green Solow Model [74], which emphasizes possible emission reductions from exogenous technological development in the pollution diminution process, the outcome helps to prescribe the need to invest in technologies that help to control pollution.

In totality, it must be noted that the country's (i.e., France) current over-reliance on nuclear power indicates its low-carbon electricity mix. It is, however, worth stressing that the country's successes over the period in reducing carbon dioxide emissions were a combined result of both its green electricity policies and historical reliance on nuclear power. It is proper to remark that the low-carbon nature of the nuclear fleet provided a strong foundation for green electricity policies to build on, although this was a unique energy context that could not be easily replicated by other countries.

Given this result, it is instructive to remark that the development of green electricity (such as wind, solar, and hydro) could further reduce the need for fossil fuel-based electricity generation in the country, particularly during peak demand of electricity, or periods when nuclear plants are being maintained. In effect, current policy directions to transition to green electricity in the energy sector support France's commitment to achieving carbon neutrality by 2050 (i.e., policies promoting green electricity, such as subsidies for renewables and grid-integration targets). This is crucial for meeting national and European climate targets. Additionally, developing a robust green electricity sector has significant geopolitical and economic implications for France, since by increasing its domestic renewable energy production, the country reduces its dependence on imported fossil fuels (such as natural gas and oil) and improves its energy security—making it less vulnerable to international price shocks and supply disruptions. These notwithstanding, experts warn that the intermittent nature of solar and wind power pose a significant challenge for the electricity grid, requiring heavy investments in smart grid technologies and energy storage solutions that can ensure a stable and reliable electricity supply [75], despite their inherent challenges [76].

Third, the findings of the N-ARDL long-run cointegration estimates (Table 5) show that the long-term coefficient of LCO_2 is affected by LPEC in both positive and negative non-linear ways. The coefficients are both significant, at 0.882688 and 1.341291, respectively. These show that, in the context of France, all other things being equal, a 1% increase in LPEC causes an increase in LCO_2 of about 88.26% during its positive shock periods, while a 1% decrease in LPEC causes an unexpected decrease in LCO_2 of 1.34% during its negative shock periods. In contrast to positive shock periods, negative shock periods for LPEC

contribute to a decrease in carbon emissions in France, confirming the theory developed for this French investigation. It is instructive to observe that primary energy use in France reached a total of 8.66 exajoules in 2023, representing a rise of five percent compared to the previous year. Although the state of France's PEC is low compared to other EU economies, France's economy slowed down significantly from 2022 until the second half of 2023, when it was expected to recover, due to supply bottlenecks and rising energy costs leading to increased coal use in electricity production. However, during the year 2000, the European nations' primary energy consumption decreased by 2.7 exajoules, reaching a peak of around 11.4 exajoules in 2004. Before being converted into electricity or other secondary or tertiary energy forms, primary energy is defined as energy that is directly extracted from natural resources, including both fossil fuels and renewable resources.

In effect, France's primary energy consumption mix has led to both significant decarbonization of its electricity sector, but also resulted in certain environmental challenges. For instance, by avoiding coal and gas for electricity, France has largely bypassed the air pollution issues (which negatively affect public health, reducing respiratory and cardiovascular diseases) currently plaguing several other industrialized nations. Notwithstanding, while nuclear power is clean in terms of air emissions, it presents unique environmental challenges such as the generation of radioactive waste, thermal pollution, and has potential for a catastrophic nuclear accident (such as those which occurred in Chernobyl or Fukushima), representing an immense environmental risk to the economy of France. Additionally, the use of nuclear power by France makes its electricity mix low-carbon, but the development of green electricity (such as wind and solar) is viewed as an important step to further reduce fossil fuel consumption, and facilitate the achievement of its carbon neutrality goals by 2050. Despite the fact that nuclear-based energy mixes have been effective in generating low-carbon electricity, their generalizability to fossil-dependent economies and policy actions is limited due to the country's unique historical, political, and economic contexts. Researchers have argued that the effectiveness of France's green electricity policies is more limited in other key sectors that are not easily electrified, such as the transport and agriculture sectors [77,78]. While policies like bonuses for electric vehicles have shown some success, they have not fully offset the rise in emissions from transportation due to increased consumption and a reliance on internal combustion engine vehicles. The agricultural sector also continues to be a major source of emissions, which green electricity policies do little to address.

Fourth, the N-ARDL long-run equilibrium estimates (Table 5) point to a positive and negative non-linear causal impact on LCO_2 as ETAX has coefficients -0.043468 and 0.064726 during positive and negative economic shocks, respectively. These imply that a 1% increase in ETAX causes a decrease in LCO_2 by approximately -0.043468% at positive shock periods, while a 1% decrease in ETAX during negative shock periods leads to a reduction in LCO_2 by 0.064726% as they move in a similar direction. This finding corroborates the hypothesis established on ETAX on LCO_2 for the case of France. Theoretically, investments in environmental tax tend to cause a reduction in CO_2 by affecting a fall in fossil fuel consumption [5]. The economy pledged to enact environmental tax laws to meet the Paris Climate Agreement and Kyoto Protocol's carbon emission reduction targets. Theoretically, if the production or consumption of specific goods results in a negative externality, then ecological taxes are justified as enhancing social welfare [17]. Theoretically, it proves that environmental pollution is a social concern because of emissions dependent on consumption or on the failure of prices in production costs. Given the difference between the private and social costs of pollution, Ref. [12] argued that taxing pollution ensures efficient market outcomes while equating private costs and social marginal damage. It is important to

recognize that France committed to transforming its energy system by curbing fossil fuel consumption with an environmental tax with the aim of realizing a transition to net zero.

In sum, environmental taxes for the economy of France have a mixed effect on environmental quality: by successfully reducing some pollutants, but with significant economic and social challenges that limit their overall impact. In practical terms, environmental taxes are generally based on the “polluter pays” principle, which creates a financial incentive for companies and individuals to change their behavior. However, experts argue environmental taxes, especially on energy and transport, tend to be regressive, disproportionately affecting lower-income households [7,8]. Since a larger share of their income is spent on necessities like heating and fuel for commuting, they bear a heavier burden from these taxes than wealthier households. Similarly, there are other scholars who have found environmental taxation to differ across economies for various context-specific factors [79,80]. In the case of France, recent environmental tax policy was limited in effectiveness due to the “Yellow Vests” protests that began in late 2018 as a direct response to a planned increase in fuel taxes (specifically on diesel) intended to fund green initiatives and reduce fossil fuel demand. However, it was perceived to disproportionately impact low- and middle-income households (particularly those in rural and suburban areas) who rely on cars for commuting and daily life. The protests forced the government to suspend and eventually cancel the planned tax hikes, demonstrating a significant political and social limitation on the effectiveness of environmental tax policies for reducing CO₂ emissions. Through these mechanisms, we find that the asymmetric response in France’s environmental taxation responses was generally not a chemical mechanism but motivated by both socio-behavioral and economic factors. Figure 3 shows the summary of the estimated nonlinear model.

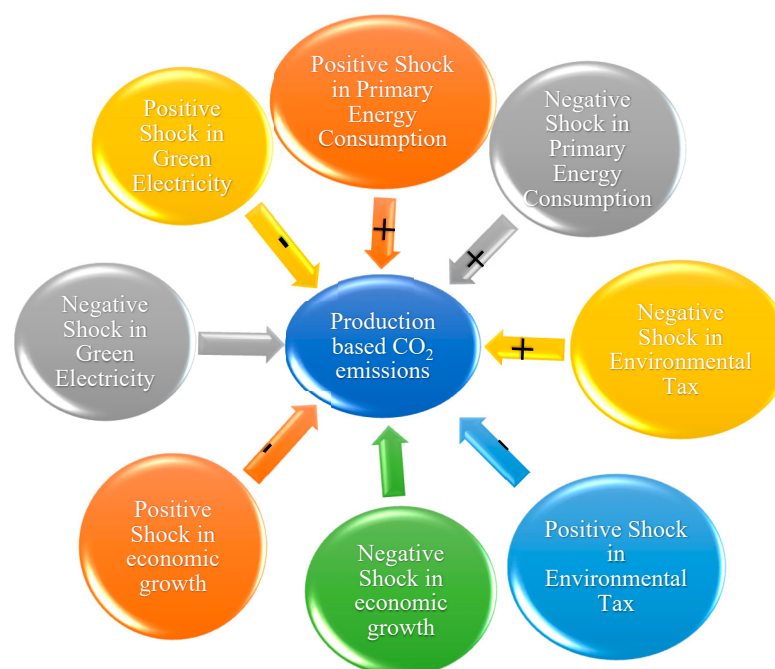


Figure 3. Empirical outcomes.

Our asymmetric results for environmental taxes suggest that policy reversals during negative shocks—often driven by distributional concerns and social resistance—can reduce their effectiveness. This underlines the need to strengthen public acceptance and equity considerations in tax design, consistent with recent debates on the regressive nature of energy taxes in France.

4.2. Broader Implications of the Study

In the future, it will be possible to explore the complex, dynamic relationship between environmental taxes, the adoption of green electricity, and the quality of the environment beyond simple cause-and-effect analyses. There is an opportunity to investigate whether France's current environmental taxes are causing a "green paradox", where the announcement of future, stricter taxes accelerates the extraction and consumption of fossil fuels in the short term, thus worsening environmental quality before it improves. By analyzing the behavior of energy-intensive industries and their investment cycles in response to policy announcements, this can be accomplished.

Additionally, several experts have warned that the effectiveness of environmental taxes and green electricity policies is not isolated but depends on their integration with other policy instruments [81,82]. Based on this observation, future research can analyze the synergies and conflicts between, for instance, (i) fiscal policy (e.g., environmental taxes) and regulatory instruments (e.g., building efficiency standards); and (ii) relations between subsidies for green technology (such as heat pumps and electric vehicles) and market-based tools (e.g., taxes). By detecting the outcomes of environmental policy mixes (i.e., carbon pricing, direct subsidies, and public investment), it will be possible to accurately detect optimized environmental outcomes in specific sectors such as transport or housing.

4.3. Model Diagnostic Tests

Model stability has historically been considered essential in econometric analysis. To ensure that the coefficient estimates are acceptable for LCO₂ policy recommendation in France, model stability has to be stable. To determine model stability, cumulative stability (CUSUM and CUSUM of squares) tests are used [83]. Furthermore, the Breusch–Godfrey serial correlation LM test and the residual diagnostic test are used to verify serial correlation and heteroskedasticity, respectively.

Based on the outcomes of serial correlation, heteroskedasticity, and Ramsey reset tests (Table 6), the model is free from both serial correlation and heteroskedasticity, given that the null hypotheses in both cases cannot be rejected, per the *p*-value. Again, the outcomes of the Ramsey reset, the model has no specification error or omitted variable bias; and the non-linear combinations of the explanatory factors help to explain the response factor, given that the probability value is insignificant.

Table 6. Serial correlation, heteroskedasticity, and Ramsey RESET tests.

Serial Correlation Test			
F-statistic	0.000673	Prob.	0.9794
Heteroskedasticity Test: Breusch-Pagan-Godfrey			
F-statistic	1.287924	Prob. F(28,70)	0.1964
Ramsey RESET Test			
	Value	df	Probability
t-statistic	1.301492	69	0.1974

Econometric scientists have historically agreed that model stability and residual diagnostic tests are essential. To improve the quality of the environment in France, coefficient estimates of the error-correction framework must be stable for meaningful policy recommendations [83]. Both CUSUM and CUSUM of squares assessments point to model estimates lying within acceptable limits (see Figures 4 and 5, respectively). In both tests, 5% confidence bands are set and, given that the CUSUM and CUSUM-squared plots remain entirely within the 5% confidence bands, the null hypothesis cannot be rejected, suggesting

that, respectively, the model's coefficients are stable with no significant structural break or change in the coefficients; and the variance of the residuals is stable over the sample period (i.e., the model is homoscedastic). Table 7 shows Fourier Toda Yamamoto causality test results. The test results indicate that all the variables, i.e., LGDP, GELEC, ETAX, and LPEC, cause LCO_2 .

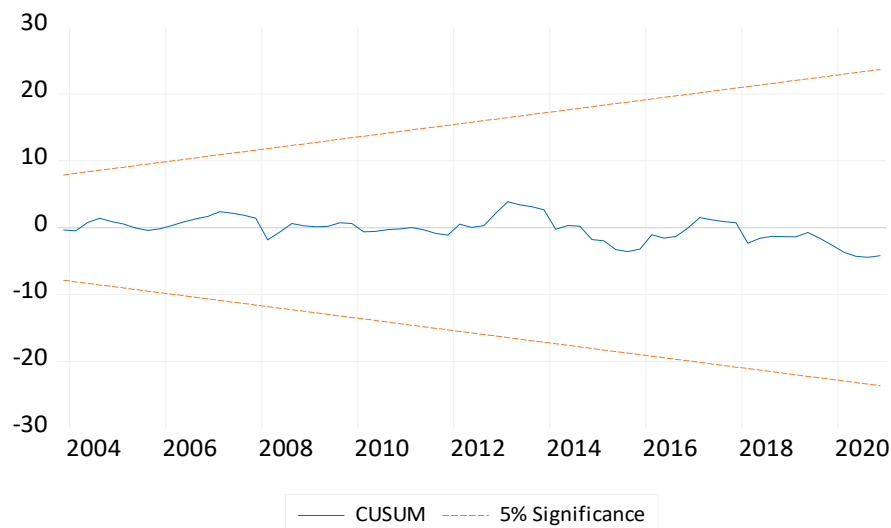


Figure 4. CUSUM.

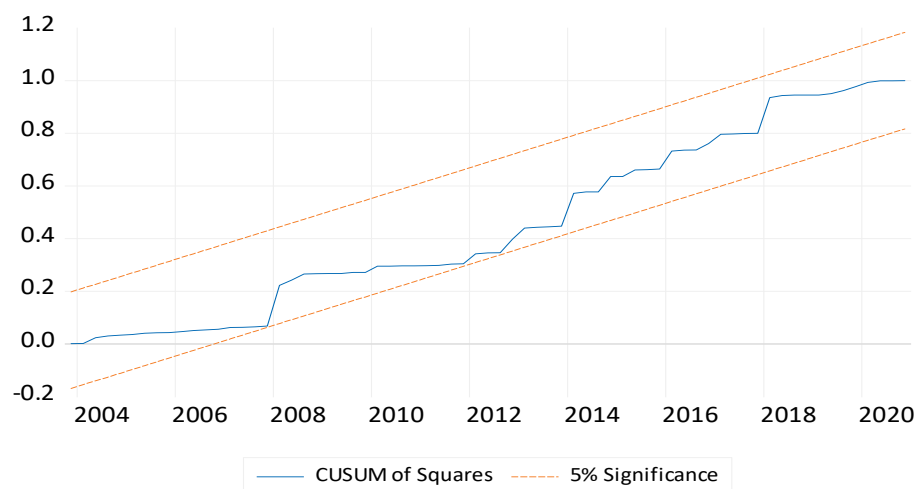


Figure 5. CUSUM of squares.

Table 7. Fourier Toda Yamamoto causality test.

	Hypothesis	T-Stat	p-Value
H_{01}	GELEC does not cause LCO_2	11.6934	0.0392
H_{02}	ETAX does not cause LCO_2	8.4206	0.0773
H_{03}	LPEC does not cause LCO_2	3.1387	0.0678
H_{04}	LGDP does not cause LCO_2	9.5878	0.0877

5. Conclusion and Implications of Study

Never before has the world been exposed to pollution and degradation as it has in the last industrial age. In recent decades, global attention has been drawn to the need to take steps to rebalance the rate of environmental degradation. To provide policy insights,

the study seeks to investigate the effect of environmental taxes and green electricity on the quality of the environment in France. The results of the N-ARDL long-run cointegration estimates reveal (i) environmental tax contributes to decreasing production-based carbon emissions; (ii) green electricity also participates in causing a fall or rise in production-based carbon emissions in France; (iii) both economic growth and primary energy consumption tend to degrade the quality of the environment; (iv) finally, the Fourier Toda Yamamoto causality test indicates all the variables, i.e., LGDP, GELEC, ETAX, and LPEC, cause LCO₂.

It is useful to recognize that although the causality estimates imply no rebound effect of both ETAX and GALEC, their paper does not, by this outcome, infer nonexistence of Jevons' Paradox, which contradicts the nonlinear outcomes of long-run Fourier ARDL estimates. In fact, there is no evidence that the Jevons Paradox is contradicted by a causality test (which only detects "predictive causality"), finding a lack of rebound effect [84]. This is due to the fact that these two concepts operate on different time horizons and scales. Jevons' Paradox is the extreme case in which increased efficiency leads to an overall increase in consumption. The rebound effect occurs when efficiency gains are partially offset by increased consumption, while Jevons' Paradox occurs when improvements in efficiency lead to an overall increase in consumption. In effect, Jevons' Paradox explains a system-wide phenomenon that includes effects beyond a simple cause-and-effect relationship between two variables. Further, it could be inferred from the outcomes of the BDS estimates where the hypothesis is rejected, indicating the existence of non-linear patterns (no rebound effect) in the variable of interest, or in the causality estimates, the relationship between efficiency and consumption is roughly proportional, appearing to be at odds with the Jevons Paradox framework.

It is also informative to observe that, in particular, France's reliance on nuclear power gives it a low-carbon electricity mix, but the development of green electricity (like wind and solar) is seen as a key step to further reduce the use of fossil fuels. This transition is crucial for the country to meet its carbon neutrality goals by 2050. However, it is worth noting that, given the country's unique historical, political, and economic context, although a nuclear-reliant energy mix has been effective in providing a low-carbon power supply, this has very limited generalizability to fossil-dependent economies and policy actions. Similarly, in this study, environmental taxes in France have a mixed effect on environmental quality, indicating that they are, in part, very effective because they follow the "polluter pays" principle, creating a financial incentive for companies and individuals to change their behavior. However, a major challenge is their regressive nature as they disproportionately impact low-income households, who spend a larger portion of their income on necessities like fuel and heating, which can lead to social and political backlash.

For policy insights, it is instructive to recognize that towards realizing the European Green Deal objectives, the European Union (EU) has set ambitious targets to deal with climate change and to preserve the quality of the environment with a 55% reduction in GHG emissions by 2030 and to become a climate-neutral continent by 2050. To deliver this emissions target, France could commit to green taxation in support of EU climate and energy strategies such as the EU Emission Trading System. In such regard, due to cross-country factors, France could work with the EU to harmonize institutional frameworks on environmentally-driven taxes that deliver EU climate objectives. Additionally, compared to other EU economies, France has been characterized by low-rate transport sector taxes. Although the "bonus-malus" system of France has been successful in carbon emission reduction on new vehicles, it has suffered significant rebound effects. France could reverse this by introducing environmental taxes, including energy-use taxes based on the CO₂ content of fossil fuels. Our findings highlight that, unlike the "bonus-malus" system, which experienced rebound effects via increased car ownership and mileage, environmental taxes

exert a more consistent influence on emissions. Future research could explicitly integrate transport indicators such as mileage or vehicle stock data to better quantify these rebound dynamics. Historically, France introduced a tax on polluting activities (TGAP) by the Finance Act of 1999 on corporations whose activities or products cause pollution.

In France, the energy sector is responsible for approximately 11% of total GHG emissions. In 2023, the economy's electricity mix is composed of 92% decarbonized production (i.e., 65% nuclear sourcing, 15% solar and wind sources, 12% hydro sourcing). Huge investments were made after a poor performance in 2022. These investments were made in 2023 knowing that the country was heavily reliant on fossil fuels, which accounted for half of its primary energy consumption. The country's investments in low-carbon energy sourcing involved hiking solar-power capacity from 16 GW to 60 GW in 2030, and wind to 35 GW in 2030; while hydroelectricity is set from 26 GW currently to 29 GW in 2035. Given the outcome of the study, France should commit to her alternative energy plan of 560 TWh of decarbonized electricity yearly from 463 TWh currently.

The key theme in France's 2025 fiscal policy is balancing deficit reduction with continued climate investment. The government's approach seems to be a mix of targeted taxes and adjustments to existing tax regimes, rather than a broad-based carbon tax increase. To further strengthen the link between taxation and environmental outcomes, France could introduce a more direct and transparent carbon pricing mechanism for businesses, possibly by aligning with a strengthened EU Emissions Trading System (ETS). Similarly, France's strategy for green electricity in 2025 is a continuation of its long-term policy, with a dual focus on nuclear energy and accelerated renewable deployment. The government of France could ensure that policies and regulations, particularly at the EU level, treat low-carbon hydrogen produced with nuclear power on par with that produced with renewables. This leverages France's existing low-carbon nuclear fleet to accelerate the green transition.

Toward detecting policy outcomes of these variables through policy combinations, policymakers' understanding of individual and corporate responses to price signals of environmental taxes is significant. In future studies, experts could investigate how (i) psychological factors and information provision influence green electricity adoption and energy-efficient practices; (ii) consumer and producer responses to sustained price signals in the economy; (iii) the interaction of EU policies (e.g., EU Emissions Trading System) and national environmental taxes (France) toward influencing markets for green energy and the decarbonization strategies of corporations.

The paper is restricted to using CO₂ emissions as the sole proxy for the environmental quality of France. This limits the quality of outcomes of the study because the use of CO₂ emissions alone oversimplifies a complex environmental system and overlooks other critical environmental issues. A future study should move beyond CO₂ emissions to include other critical metrics of environmental quality towards providing a more holistic and accurate picture of France's environmental health. Additionally, given the time constraints, the paper could not assess the quality of the environment concerning economies outside France. It is suggested that future studies could consider investigating cross-regional comparisons from the perspective of these variables using many more economies for comparative purposes. Moreover, future research could extend our framework by incorporating multiple indicators of environmental quality—such as air pollution metrics, biodiversity loss, or composite environmental indices—to provide a more holistic and robust assessment of policy impacts.

Further, given that France's industrial and transport sectors contribute significantly to carbon emissions, this study is limited by failing to provide deeper insight into the impacts of both environmental tax and green electricity investments. Future studies should consider

investigating disaggregating CO₂ data by sectors to detect this either in France or other economies to make definitive recommendations for policy action.

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