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Ecological Roles of Green Finance, Economic Growth, and Clean Energy Use: The Moderating Role of Institutional Quality

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Abstract

Environmental sustainability remains a critical challenge for member countries of the Organisation for Economic Co-operation and Development (OECD), where advanced economic structures coexist with high levels of resource consumption and ecological pressure. This study contributes to the literature by integrating green finance, economic growth, renewable energy consumption, and institutional quality within a unified framework, with particular emphasis on the moderating role of institutional quality in the relationship between these factors and ecological sustainability, measured by the Load Capacity Factor (LCF). Using a balanced panel dataset of 20 OECD countries over the period 2010 to 2023, the study employs the System Generalized Method of Moments (System GMM) to address endogeneity and account for dynamic relationships. The findings reveal that economic growth initially deteriorates ecological sustainability, although a nonlinear U-shaped relationship supports the Load Capacity Curve (LCC) hypothesis. Green finance, renewable energy consumption, and institutional quality all exert positive and statistically significant effects on the LCF. Importantly, the interaction results indicate that institutional quality strengthens the positive effects of both green finance and renewable energy consumption on ecological sustainability. These findings suggest that policy effectiveness depends not only on financial and energy reforms but also on institutional capacity. Accordingly, strengthening governance frameworks alongside green investment is essential for achieving sustainable development.

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1. Introduction

Environmental quality has emerged as a central concern in advanced economies, particularly within OECD countries, where high levels of industrialization and energy consumption exert significant pressure on ecological systems [1, 2]. Despite their technological advancement and regulatory capacity, these economies continue to face challenges in balancing sustained economic growth with environmental sustainability [3, 4]. The interaction between economic activity and environmental degradation remains complex [5–7], as growth-driven production and consumption often lead to increased resource depletion and emissions. Although advanced economies are expected to achieve environmental improvements at higher income levels, empirical evidence suggests that the transition toward sustainable growth is neither automatic nor uniform [8–11]. Therefore, understanding the determinants of environmental quality in OECD countries is crucial, especially when considering broader indicators such as the Load Capacity Factor (LCF), which provides a more

comprehensive assessment of ecological sustainability beyond conventional emission-based measures.

Green finance has gained increasing attention as a critical mechanism for promoting environmental sustainability by redirecting financial resources toward low-carbon and environmentally friendly investments [12]. In OECD countries, where financial markets are well-developed, green financial instruments such as green bonds, sustainable lending, and climate-focused investment funds play a pivotal role in facilitating the transition toward a greener economy. These instruments help reduce environmental degradation by supporting renewable energy projects, energy-efficient technologies, and sustainable infrastructure development. However, the effectiveness of green finance largely depends on the institutional environment, including regulatory frameworks, transparency, and governance quality [13, 14]. Without strong institutional support, issues such as misallocation of funds and greenwashing may reduce its environmental impact. Moreover, existing studies suggest that the marginal effectiveness of green finance may decline in highly polluted environments, highlighting the need for complementary policy mechanisms [15].

Economic growth remains a fundamental driver of environmental change, often exerting both positive and negative effects on environmental quality [16–18]. On one hand, economic expansion increases energy demand, industrial activity, and resource utilization, which typically lead to higher emissions and environmental degradation. On the other hand, higher income levels can facilitate investments in cleaner technologies, stricter environmental regulations, and improved environmental awareness. The Environmental Kuznets Curve (EKC) hypothesis suggests that environmental degradation initially increases with economic growth but eventually decreases after reaching a certain income threshold. However, empirical findings across different countries remain inconclusive [19–22]. Even in OECD countries, where technological progress is relatively advanced, economic growth continues to pose environmental challenges. This underscores the importance of examining how growth interacts with other factors such as green finance and energy transition in shaping environmental outcomes.

Renewable energy consumption is widely recognized as a key pillar of sustainable development and environmental improvement [23–26]. The transition from fossil fuels to renewable energy sources such as solar, wind, and hydropower significantly reduces carbon emissions and enhances ecological sustainability. OECD countries have been at the forefront of this transition, investing heavily in clean energy technologies and infrastructure. Empirical evidence consistently demonstrates that increasing the share of renewable energy in the energy mix leads to substantial reductions in environmental degradation [27]. However, the effectiveness of renewable energy adoption varies across countries due to differences in technological capacity, resource availability, and policy frameworks. Therefore, understanding the role of renewable energy consumption in improving environmental quality requires a nuanced analysis that accounts for such heterogeneity.

Institutional quality plays a crucial role in shaping environmental outcomes by influencing the effectiveness of economic, financial, and energy-related policies. Strong institutions, characterized by transparency, regulatory enforcement, and low corruption, enhance the implementation of environmental policies and ensure the efficient allocation of resources [28–30]. In OECD countries, institutional quality is generally high, yet variations still exist, affecting the performance of environmental strategies. Importantly, institutional quality not only has a direct impact on environmental quality but also acts as a moderating factor that influences how green finance and renewable energy contribute to sustainability. In well-governed environments, financial resources are more likely to be allocated efficiently, and renewable energy policies are implemented more effectively [15]. This highlights the importance of examining both the direct and indirect (moderating) effects of institutional quality in the environmental sustainability framework.

The selection of OECD countries as the focus of this study is motivated by their distinctive economic, institutional, and environmental characteristics. These countries generally have advanced financial systems, strong regulatory frameworks, and significant technological capabilities, making them a relevant setting for examining the relationship between green finance, economic growth, renewable energy consumption, and ecological sustainability. Nevertheless, environmental challenges persist despite these advantages. According to the OECD, fossil fuels accounted for 76.6% of total energy supply in OECD countries in 2024, while renewable energy accounted for only 13.1%, highlighting the continuing challenge of transitioning toward cleaner energy systems [31]. These challenges underscore the importance of examining not only the direct environmental contributions of green finance and renewable energy but also the institutional conditions under which these contributions may be strengthened [32]. Although previous studies have examined the environmental implications of economic growth,

renewable energy, and financial development [13, 27], further investigation is needed into the moderating role of institutional quality in the relationship between these sustainability drivers and the Load Capacity Factor (LCF). Moreover, Akram et al. [33] emphasized that institutional factors play a critical role in determining the success of environmental policies and financial interventions. Therefore, focusing on OECD countries enables a comprehensive and policy-relevant analysis of sustainable development dynamics in advanced economies.

This study contributes to the existing literature in several important ways. First, it employs the LCF as a comprehensive indicator of environmental quality, moving beyond traditional measures such as CO_2 emissions and providing a more holistic perspective on ecological sustainability [8]. Second, it integrates multiple key determinants, green finance, economic growth, renewable energy consumption, and institutional quality, within a unified analytical framework, addressing the limitations of prior studies that examine these factors in isolation. Third, the study introduces the moderating role of institutional quality, specifically investigating how governance structures influence the effectiveness of green finance and renewable energy in improving environmental quality. This moderating analysis represents a significant advancement in understanding the conditional effects of sustainability drivers. Fourth, by focusing on OECD countries, the study offers insights into the environmental dynamics of advanced economies, contributing to policy design in high-income contexts. Collectively, these contributions provide a more comprehensive and nuanced understanding of the determinants of environmental sustainability.

The primary research objectives of this study are centered on examining the key determinants of environmental quality in OECD countries, with a particular focus on green finance, economic growth, renewable energy consumption, and institutional quality. In this context, the study aims to provide a comprehensive analysis of how these factors influence the LCF as a multidimensional indicator of ecological sustainability. Specifically, the research seeks to evaluate both the individual and joint effects of these variables on environmental quality, while also exploring the underlying mechanisms through which these relationships operate. A central aspect of this investigation is the role of institutional quality, not only as a direct determinant of environmental outcomes but also as a conditioning factor that may enhance or constrain the effectiveness of green finance and renewable energy consumption. In particular, the study examines whether stronger institutional frameworks improve the allocation efficiency of green financial resources and facilitate the successful implementation of renewable energy policies. Additionally, it explores the nature of the relationship between economic growth and environmental sustainability in advanced economies, where structural and technological factors may alter conventional patterns observed in developing contexts. Accordingly, the research is guided by a set of interrelated questions concerning whether green finance contributes to improving environmental quality, how economic growth affects ecological sustainability, the extent to which renewable energy consumption mitigates environmental degradation, and how institutional quality influences these dynamics both directly and indirectly. Furthermore, the study investigates whether institutional quality moderates the impact of green finance and renewable energy consumption on environmental quality, thereby offering deeper insights into the governance mechanisms that shape sustainable development pathways in OECD countries.

2. Literature Review and Research Gaps

2.1. Empirical Review

The relationship between economic activity and environmental quality has long been a central theme in environmental economics. Traditional perspectives emphasize that economic growth leads to increased environmental degradation due to higher energy consumption, industrial expansion, and resource exploitation. This view is formalized in the EKC hypothesis, which posits an inverted U-shaped relationship between income and environmental degradation. While early stages of growth are associated with rising emissions, higher income levels may eventually lead to environmental improvements through technological advancement and stricter regulations. However, empirical evidence remains mixed, particularly across advanced economies, where the turning point of the EKC is not consistently observed [11, 34]. Recent studies suggest that the growth-environment nexus is highly contingent upon structural transformation, energy composition, and institutional settings rather than income levels alone. In this context, renewable energy consumption has emerged as a critical factor in mitigating environmental degradation. A substantial body of literature demonstrates that increasing the share of renewable energy in the energy mix significantly reduces carbon emissions and improves environmental quality. For instance, Dong et al. [27] provide global evidence that renewable energy consumption contributes to lowering CO_2 emissions across countries with varying income levels. Similarly, Akram et al. [33]

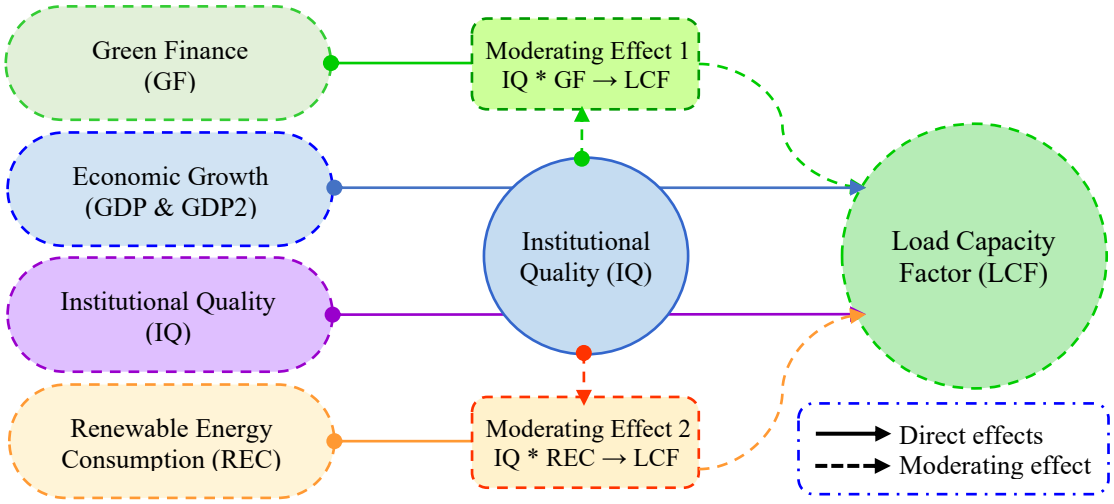


Figure 1. Conceptual framework of the study.

highlight that energy efficiency and renewable energy adoption jointly reduce environmental pressure in developing economies. Despite these findings, the effectiveness of renewable energy transitions varies significantly due to differences in technological capacity, infrastructure, and policy support. This suggests that the environmental benefits of renewable energy are not uniform and depend on broader economic and institutional conditions.

Parallel to the energy transition, the emergence of green finance has introduced a financial dimension to environmental sustainability. Green finance encompasses financial instruments and policies designed to support environmentally friendly investments, including renewable energy, energy efficiency, and low-carbon technologies. Empirical studies indicate that green finance plays a significant role in reducing environmental degradation by channeling capital toward sustainable projects [13]. However, the effectiveness of green finance is not guaranteed. Issues such as greenwashing, inefficient capital allocation, and diminishing marginal returns have been highlighted in recent literature [15]. Moreover, the impact of green finance appears to be conditional on the quality of governance structures, suggesting that institutional factors play a crucial role in determining its success. Institutional quality has increasingly been recognized as a key determinant of environmental performance. Strong institutions, characterized by effective governance, transparency, and regulatory enforcement, enhance the implementation of environmental policies and improve resource allocation efficiency. Empirical evidence suggests that higher institutional quality is associated with lower emissions and better environmental outcomes [35]. Furthermore, institutions can influence environmental quality indirectly by shaping the effectiveness of other factors such as green finance and renewable energy adoption. For example, well-functioning institutions can facilitate the efficient deployment of financial resources and ensure that renewable energy policies are effectively implemented. Conversely, weak institutional frameworks may undermine these efforts, leading to suboptimal environmental outcomes.

2.2. Research Gaps and Conceptual Framework

Despite the growing body of literature on these individual relationships, several important gaps remain. First, most studies focus on single determinants of environmental quality, such as economic growth, renewable energy, or green finance, without considering their joint interactions. Second, limited attention has been paid to the role of institutional quality as a moderating factor that influences the effectiveness of green finance and renewable energy consumption. Third, many existing studies rely on traditional environmental indicators such as CO_2 emissions, which may not fully capture ecological sustainability. The use of broader measures, such as the LCF, remains relatively underexplored. Finally, there is a lack of comprehensive analysis focusing specifically on OECD countries, where advanced financial systems, strong institutions, and ongoing energy transitions create a unique context for studying sustainable development. Addressing these gaps, the present study develops an integrated framework that examines both the direct and moderating effects of institutional quality while employing a more comprehensive measure of environmental quality. Based on the empirical literature and the theoretical discussions presented above, the conceptual model of the study is illustrated in Figure 1. The framework highlights the direct effects of green finance, economic growth, and renewable energy

Table 1. Description of the variables.

Variables	Symbol	Description	Measurement	Source
Environmental Quality	LCF	Load capacity factor	Ratio (biocapacity / ecological footprint)	GFN [36]
Green Finance	GF	Green financial development	Index (proxy for green investments)	WDI [37]
Economic Growth	GDP	Economic activity level	GDP per capita (constant prices)	OECD [38]
Renewable Energy	REC	Clean energy utilization	Percent of total energy consumption	OECD [38]
Institutional Quality	IQ	Governance quality	Composite governance index	WGI [39]

Note: GFN means Global Footprint Network, WDI means World Development Indicators, WGI means World Governance Indicators, and OECD means Organization for Economic Co-operation and Development.

consumption on environmental quality (LCF), while emphasizing the moderating role of institutional quality in shaping these relationships.

3. Data and Methodology

3.1. Data and Variable

This study utilizes a balanced panel dataset comprising 20 selected OECD countries over the period 2010–2023, subject to data availability. The selection of OECD countries is motivated by their advanced economic structures, well-developed financial systems, and relatively high institutional quality, which provide an appropriate setting for analyzing the interplay between green finance, economic growth, renewable energy consumption, and environmental sustainability. Environmental quality, the dependent variable of the study, is proxied by Load Capacity Factor (LCF), which reflects the ecological balance between biocapacity and ecological footprint. Green finance (GF), a key explanatory variable, is measured using a composite index that captures environmentally oriented financial activities. This study relies on proxy indicators such as environmentally related financial development. Economic growth (GDP) is represented by real gross domestic product per capita (constant prices). Renewable energy consumption (REC) is measured as the share of renewable energy in total final energy consumption. Institutional quality (IQ), the moderating variable in this study, is proxied by a composite governance index. All variables are transformed into natural logarithms prior to estimation to stabilize variance, reduce heteroskedasticity, and allow for elasticity-based interpretation of the coefficients. Table 1 summarizes the definitions, measurements, expected signs, and data sources of the variables used in this study.

3.2. Model Specification and Method

This study utilizes a panel dataset of OECD countries to empirically investigate the impact of green finance, economic growth, renewable energy consumption, and institutional quality on environmental sustainability, proxied by the LCF. The adoption of panel data techniques offers several methodological advantages over purely cross-sectional analyses. Specifically, panel data enable the control of unobserved country-specific heterogeneity, enhance the variability and informational richness of the dataset, and improve the efficiency and consistency of parameter estimates. Moreover, such an approach mitigates potential biases arising from omitted variables and reduces multicollinearity among regressors, thereby yielding more reliable empirical inferences. In the presence of dynamic relationships, where the lagged dependent variable is included among the regressors, conventional estimation techniques such as Ordinary Least Squares (OLS) become inappropriate due to endogeneity, simultaneity, and autocorrelation concerns. Under these conditions, OLS estimators are biased and inconsistent. Although instrumental variable approaches, such as Two-Stage Least Squares (2SLS), may partially address endogeneity, their performance is often limited by the difficulty of identifying valid and strong external instruments, which may lead to imprecise and statistically insignificant estimates.

To overcome these econometric challenges, this study employs the Generalized Method of Moments (GMM) framework developed by Arellano & Bond [40], which is well-suited for dynamic panel data models. The GMM estimator effectively addresses endogeneity by utilizing internal instruments derived from lagged values of the explanatory variables, while also accommodating heteroskedasticity and serial correlation in the error structure. The choice of GMM is further justified by the structure of the dataset, where the number of cross-sectional units (N) exceeds the time dimension (T), a setting in which GMM estimators are particularly efficient and appropriate. Nevertheless, the conventional difference GMM estimator may suffer from weak instrument problems, especially when the variables exhibit high persistence over time. To address this limitation, the System GMM estimator proposed by Blundell & Bond [41] is employed. This approach augments the standard difference GMM by incorporating an additional set of moment conditions in levels, thereby improving instrument strength and enhancing estimation efficiency. The System GMM estimator combines equations in first differences and levels, allowing for more precise and robust parameter estimation in dynamic panel contexts. The reliability of

Table 2. Statistics for data description.

Variables	Mean	Max.	Min.	Skewness	Kurtosis	Jarque-Bera
LCF	1.89	2.22	-1.17	0.433	3.254	225.818***
GF	0.139	0.916	-0.098	3.071	15.178	5058.151***
GDP	8.801	12.81	8.184	1.088	14.51	1288.150***
REC	5.991	9.61	3.807	1.799	13.801	5058.151***
IQ	1.81	2.4	0.919	0.392	1.752	5058.151***

Note: *** indicate significant at 1% level.

the GMM estimation results is contingent upon the validity of the underlying assumptions and instruments. Accordingly, the Arellano-Bond test is conducted to verify the absence of second-order serial correlation in the differenced error terms, while the Sargan or Hansen test of overidentifying restrictions is employed to assess the overall validity of the instrument set. Given its superior efficiency and robustness relative to alternative estimators, the System GMM approach is adopted to estimate the empirical models in this study. Following the theoretical framework and drawing on established empirical literature and inspired by Fakher et al. [42], the baseline dynamic specification of the model is expressed in Equation 1.

$$lnLCF_{it} = \alpha_0 + \delta\, ln\, LCF_{i,t-1} + \theta\, ln\, X_{it} + \varepsilon_{it} \quad (1)$$

where i indexes countries and t denotes time. LCF_{it} represents environmental quality measured by the load capacity factor, and X_{it} is a vector of explanatory variables comprising green finance (GF), economic growth (GDP), renewable energy consumption (REC), and institutional quality (IQ). To capture the moderating role of institutional quality and incorporate additional determinants of environmental performance, the model is extended to Equation 2.

$$\begin{aligned} lnLCF_{it} = {} & \alpha_0 + \beta_1 lnLCF_{i,t-1} + \beta_2 lnGDP_{it} + \\ & \beta_3 lnGDP_{it}^2 + \beta_4 lnGF_{it} + \beta_5 lnREC_{it} + \\ & \beta_6 lnIQ_{it} + \beta_7 ln(GF_{it} \times IQ_{it}) + \\ & \beta_8 ln(REC_{it} \times IQ_{it}) + \varepsilon_{it} \end{aligned} \quad (2)$$

In this specification, the interaction terms $GF \times IQ$ and $REC \times IQ$ are introduced to explicitly examine the moderating effect of institutional quality on the relationship between green finance, renewable energy consumption, and ecological sustainability. Furthermore, economic growth (GDP) is included as a control variable to account for other relevant macroeconomic and structural factors that may influence ecological sustainability. This comprehensive modeling strategy allows for a more nuanced understanding of both the direct and conditional effects of the key determinants of ecological sustainability in OECD economies. The inclusion of these interaction terms also helps determine whether institutional quality enhances or weakens the contributions of green finance and renewable energy consumption to ecological sustainability.

4. Results and Discussion

4.1. Descriptive Statistics

The descriptive statistics reported in Table 2 indicate that the variables exhibit noticeable deviations from normal distribution, as evidenced by the high skewness and kurtosis values. In particular, the Jarque–Bera test statistics are statistically significant at the 1% level for all variables, leading to the rejection of the null hypothesis of normality. These results suggest the presence of non-normality, potential outliers, and distributional asymmetry in the dataset. From an econometric perspective, such characteristics justify the use of advanced estimation techniques that are robust to non-normality and heteroskedasticity. In this regard, the adoption of the System GMM estimator is appropriate, as it does not rely on strict normality assumptions and is well-suited for handling dynamic panel structures with heterogeneous distributions. Therefore, the statistical properties of the variables provide empirical support for the chosen estimation strategy and reinforce the reliability of the model specification.

4.2. System GMM Estimation and Discussion

Table 3 reports the results of the System GMM estimation, which examines the effects of economic growth, green finance, renewable energy consumption, and institutional quality on ecological sustainability, measured by LCF. The coefficient of economic growth is negative and statistically significant across all estimated specifications. This indicates that economic expansion reduces LCF in the selected OECD countries, suggesting that growth still imposes ecological pressure even in advanced economies. This result can be explained by the fact that OECD countries, despite technological progress and stronger environmental regulations, continue to rely on high levels of production, consumption, transportation, and energy use. Therefore, economic growth may increase ecological footprint faster than biocapacity, thereby reducing LCF. This finding is consistent with the argument that economic growth may intensify environmental pressure when it is not fully decoupled from resource use and energy demand. It is in line with Fakher et al. [11], who show that economic growth can generate adverse environmental

Table 3. Result of the system GMM estimation.

Variables	Model 1		Model 2		Model 3	
	Coef.	**Prob.**	**Coef.**	**Prob.**	**Coef.**	**Prob.**
lnGDP	-0.2841***	0.000	-0.2733***	0.000	-0.2608***	0.000
$lnGDP^2$	0.0891***	0.000	0.0783***	0.000	0.0961***	0.000
lnGF	0.0448***	0.003	0.0780***	0.002	0.0677***	0.003
lnREC	0.0312**	0.013	0.0490**	0.032	0.0360**	0.030
lnIQ	0.0226***	0.001	0.0381**	0.001	0.0452***	0.003
ln(GF×IQ)	–	–	0.0080**	0.033	–	–
ln(REC×IQ)	–	–	–	–	0.0060**	0.031
C	1.1820***	0.000	1.2071***	0.000	1.1609***	0.000

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

consequences depending on the environmental indicator considered. It also corresponds with Chien et al. [21], who emphasize that growth-related activities can increase environmental degradation when not supported by sufficient technological and energy transition policies. However, this result contrasts with the interpretation of the EKC hypothesis, which suggests that higher income should eventually improve environmental quality.

The positive and statistically significant coefficient of GDP squared confirms the presence of a nonlinear relationship between economic growth and LCF. Since GDP has a negative coefficient while GDP squared is positive, the findings suggest a U-shaped relationship between economic growth and ecological sustainability, confirming the load capacity curve (LCC). This means that at earlier stages or lower levels of economic expansion within the OECD sample, growth may reduce ecological sustainability, but after reaching a certain threshold, additional economic development may contribute to environmental improvement. This pattern is plausible in OECD economies because higher income levels are often associated with cleaner technologies, stricter environmental standards, stronger public demand for sustainability, and greater capacity to finance green innovation. Therefore, the result implies that advanced stages of development may help restore environmental quality when growth becomes more knowledge-based, service-oriented, and innovation-driven. This finding supports the broader view of Fakher et al. [11], who argue that the growth–environment relationship may be nonlinear and indicator-sensitive.

Green finance has a positive and statistically significant effect on LCF across the estimated models. This indicates that expanding green financial mechanisms improves ecological sustainability in OECD countries. The result is economically meaningful because OECD economies generally have sophisticated financial systems capable of mobilizing capital toward renewable energy, clean technologies, sustainable infrastructure, and environmental innovation. Green finance can improve LCF by reducing ecological pressure and supporting projects that enhance resource efficiency and low-carbon transition. This finding is consistent with Yu et al. [13], who show that financial innovation and digital finance can facilitate renewable energy development. It also supports Li & Cheng [15], who emphasize the role of sustainable finance in reducing environmental pressure by directing resources toward low-carbon projects. In the OECD context, this effect is likely stronger because financial markets are deeper, regulatory systems are more transparent, and investors increasingly integrate environmental criteria into financing decisions.

Renewable energy consumption also exerts a positive and statistically significant influence on LCF. This suggests that increasing the share of renewable energy in the energy mix enhances ecological sustainability in OECD countries. The result is consistent with the structural characteristics of these economies, where renewable energy deployment is supported by technological capacity, policy incentives, and long-term decarbonization strategies. Renewable energy reduces dependence on fossil fuels, lowers ecological footprint, and contributes to improving the balance between environmental demand and ecological capacity. This finding is in harmony with Dong et al. [27], who report that renewable energy consumption contributes to lower CO_2 emissions across countries with different income levels. It is also supported by Akram et al. [33], who demonstrate that renewable energy and energy efficiency reduce environmental pressure. Similarly, Sahoo & Sethi [43] highlight the importance of renewable energy in reducing ecological footprint, which is conceptually aligned with the positive effect found for LCF.

Institutional quality has a positive and statistically significant coefficient across the models, indicating that stronger institutions improve ecological sustainability in OECD countries. This result reflects the crucial role of governance in enforcing environmental regulations, reducing policy uncertainty, preventing greenwashing, and ensuring the efficient allocation of environmental resources. In advanced economies, institutions shape the

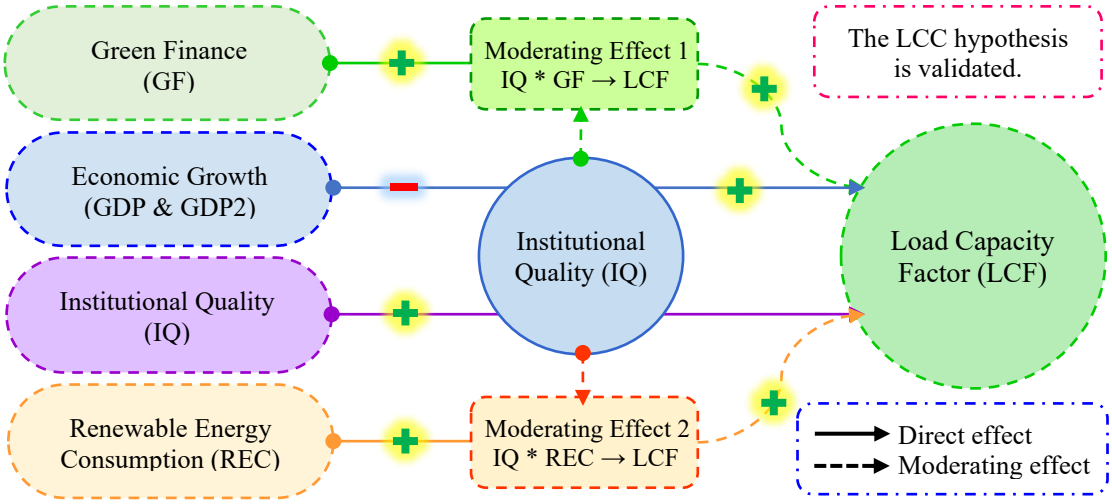


Figure 2. Graphical presentation of the empirical findings.

effectiveness of environmental policy by supporting regulatory compliance, technological innovation, and transparent financial markets. Therefore, higher institutional quality can increase LCF by strengthening the mechanisms through which economic and environmental policies are implemented. This finding is consistent with Drago & Gatto [35], who emphasize the relevance of institutional and governance-related factors in shaping environmental and energy outcomes. It also aligns with Li & Cheng [15], who argue that institutional quality enhances the effectiveness of sustainable finance and clean energy policies.

The interaction term between green finance and institutional quality is positive and statistically significant. This indicates that institutional quality strengthens the positive effect of green finance on LCF. In other words, green finance becomes more effective in improving ecological sustainability when supported by stronger institutions. This result is particularly relevant for OECD countries because the success of green financial instruments depends heavily on regulatory credibility, financial transparency, disclosure standards, and enforcement capacity. Strong institutions reduce the risk of greenwashing, improve monitoring of green investments, and ensure that financial resources are directed toward genuinely sustainable projects. Therefore, the positive interaction effect suggests that institutional quality acts as an enabling mechanism that transforms green finance into real ecological improvement.

The interaction term between renewable energy consumption and institutional quality is also positive and statistically significant. This finding implies that institutional quality enhances the environmental effectiveness of renewable energy consumption. In OECD countries, renewable energy policies require coordinated regulatory frameworks, long-term investment certainty, grid modernization, and policy consistency. Strong institutions can facilitate these conditions by improving policy implementation, reducing administrative barriers, and ensuring stable support for clean energy projects. Therefore, the positive moderating effect indicates that renewable energy contributes more effectively to LCF in countries where institutional frameworks are stronger. This result highlights that clean energy transition is not only a technological or financial process but also an institutional one.

Overall, as illustrated in Figure 2, green finance, renewable energy consumption, and institutional quality improve ecological sustainability in OECD countries, whereas economic growth initially exerts pressure on LCF. However, the positive coefficient of GDP squared suggests that, at higher levels of economic development, economic growth may become more environmentally supportive. The interaction results further reveal that institutional quality is not merely a direct determinant of environmental quality but also a strategic moderator that enhances the effectiveness of green finance and renewable energy consumption. These findings underscore the importance of integrating financial, energy, and institutional reforms to improve ecological sustainability in advanced economies.

4.3. Diagnostic Assessment

The diagnostic assessment of the System GMM estimations in Table 4 provides strong support for the adequacy and reliability of the empirical model. In particular, the presence of serial correlation in the residuals was examined using the Arellano-Bond AR(1) and AR(2) tests. The results indicate that the null hypothesis of no first-order serial correlation is rejected,

Table 4. Diagnostic assessment results for the system GMM estimation.

Diagnostic Tests	Model 1	Model 2	Model 3
Sargan Test Stat.	667.77	119.74	265.00
AR(1) Prob.	0.000***	0.000***	0.000***
AR(2) Prob.	0.589	0.707	0.819
x^2 Prob.	0.000***	0.000***	0.000***

Note: x^2 denotes the chi-square statistic. *** indicates significance at the 1% level.

as evidenced by the statistically significant AR(1) test (p-value = 0.000), which is expected in dynamic panel frameworks. More importantly, the AR(2) test, which evaluates the existence of second-order serial correlation in the differenced residuals, yields statistically insignificant results across all estimated models. This implies that the null hypothesis of no second-order autocorrelation cannot be rejected, confirming that the error terms do not suffer from higher-order serial dependence. The absence of second-order autocorrelation is a crucial condition for the validity of the moment restrictions underlying the System GMM estimator. Therefore, these findings indicate that the instruments used in the estimation are appropriate and that the dynamic specification of the model is correctly identified.

5. Conclusion and Practical Recommendations

5.1. Conclusion

This study examines the effects of green finance, economic growth, renewable energy consumption, and institutional quality on ecological sustainability in 20 OECD countries over the period 2010-2023 using the System GMM approach. The results show that economic growth has a negative and statistically significant effect on the Load Capacity Factor (LCF), while its squared term is positive and significant, indicating a U-shaped relationship and supporting the Load Capacity Curve hypothesis. Green finance, renewable energy consumption, and institutional quality exert positive and statistically significant effects on the LCF. Furthermore, the positive and significant interaction terms between institutional quality and both green finance and renewable energy consumption indicate that stronger institutions enhance the ecological benefits of these two factors. Overall, the findings demonstrate that ecological sustainability in OECD countries is associated not only with green finance and renewable energy development but also with institutional quality, which strengthens their positive environmental contributions.

5.2. Practical Recommendations

Based on the empirical findings, several policy recommendations are relevant for OECD countries. First, governments should strengthen green financial markets by expanding green bond issuance, sustainability-linked lending, and institutional investment in renewable energy and energy-efficient infrastructure. To ensure that these instruments generate genuine environmental benefits, policymakers should improve environmental disclosure requirements, strengthen independent verification of green investments, and enforce consistent green-finance taxonomies to reduce greenwashing and improve capital allocation. Second, governments should accelerate renewable energy deployment through investment in electricity grids, cross-border interconnections, energy storage, and permitting reforms, while adapting policy instruments to differences in national energy systems and renewable resource availability. The positive moderating effect of institutional quality further highlights the importance of effective regulatory enforcement, transparent public procurement, and stable policy frameworks in ensuring that financial support and renewable energy programs deliver measurable ecological improvements. Third, given the U-shaped relationship between economic growth and the Load Capacity Factor, OECD policymakers should not assume that higher income automatically improves ecological sustainability. Instead, they should promote low-carbon industrial transformation, circular-economy practices, energy efficiency, and the decoupling of economic output from resource consumption and ecological pressure. Finally, governments should strengthen coordination between financial regulators, energy authorities, and environmental agencies to align investment incentives, energy-transition strategies, and environmental standards. Such an integrated policy approach can help OECD economies translate their financial and technological advantages into sustained improvements in ecological sustainability.

5.3. Limitations and Future Research Directions

This study has several limitations that provide directions for future research. First, the analysis covers 20 OECD countries over the period 2010-2023, which may limit the generalizability of the findings to other economic contexts. Future studies should extend the analysis to non-OECD and developing economies to determine whether the relationships identified in this study differ across income levels and institutional settings. Second, green finance is measured using proxy indicators that

may not fully capture its multidimensional nature. Future research should employ more direct and comprehensive measures, such as green bond issuance, green lending, and climate-related investment, to assess whether different forms of green finance have distinct environmental effects. Third, the results may be sensitive to instrument selection and model specification under the System GMM approach. Future studies should test the robustness of the findings using alternative estimators, carefully control instrument proliferation, and report comprehensive instrument-validity diagnostics. Fourth, ecological sustainability is assessed using the Load Capacity Factor (LCF) alone. Future research should incorporate alternative environmental indicators, such as ecological footprint and planetary pressures-adjusted measures, to determine whether the findings remain consistent across different dimensions of environmental sustainability. Finally, this study focuses on the moderating role of institutional quality in the relationships between green finance, renewable energy consumption, and ecological sustainability. Future studies should investigate additional conditioning factors, particularly technological innovation, environmental policy stringency, and financial development, and apply nonlinear or threshold models to identify the institutional and economic conditions under which these relationships become stronger or weaker.

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