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Sustainable Financing and Eco-Innovation as Drivers of Low-Carbon Transition: Empirical Evidence from Tunisia

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Abstract

Many emerging economies seek to lower carbon intensity while remaining heavily dependent on fossil fuels. This paper examines how sustainable finance, eco-innovation, and the energy mix shape Tunisia's low-carbon transition. We use quarterly data for 2000–2023 and an econometric environmental-impact model that links carbon intensity to green finance, innovation, renewable and fossil energy, openness, income, and demographic factors. The results show that sustainable finance consistently reduces carbon intensity across all emission states, with stronger effects when emissions are high. The energy mix is crucial: a larger share of renewable energy lowers carbon intensity, while higher fossil energy use increases it and reinforces fossil carbon lock-in. Eco-innovation has its strongest mitigation effects in high-intensity situations, suggesting delayed effects linked to limited absorptive capacity and technology diffusion. Openness and demographic pressure tend to raise emissions through scale and consumption channels. Overall, the findings depict a finance-anchored but energy-constrained transition. They indicate that Tunisia and similar MENA economies can accelerate decarbonization by scaling credible sustainable finance instruments, speeding up renewable deployment, and strengthening the innovation and governance framework that supports green investment, innovation policy, and energy sector reform in semi-industrialized economies.

Keywords: sustainable finance; eco-innovation; carbon intensity; quantile regression; environmental Kuznets curve; renewable energy; fossil energy; trade openness; Tunisia

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1. Introduction

Achieving environmental sustainability has become a defining development challenge for semi-arid and climate-exposed economies such as Tunisia. Multiple stressors, including water scarcity, coastal erosion, and episodic flooding, interact with a persistent reliance on fossil fuels, heightening both physical and transition risks (IPCC, 2022; Arora et al., 2018; McCollum et al., 2014). If left unaddressed, these pressures risk locking in high-carbon infrastructure and eroding welfare through productivity losses, health impacts, and exposure to energy-price volatility. The issue is further intertwined with global commitments under the Paris Agreement and Sustainable Development Goal 13, which call for decisive national strategies to mitigate and adapt to climate change.

Country-specific anchors highlight the scale and urgency of the transition. The Government of Tunisia aims to reach 35 percent renewable capacity in electricity generation by

2030 and 50 percent by 2035 (World Bank, 2024). Yet the energy mix remains overwhelmingly fossil-based, around 97 percent, and largely natural gas, with nearly half of the gas needs imported (U.S. Department of Commerce, 2024). In its updated nationally determined contribution (NDC), Tunisia commits to reducing emissions intensity by roughly 45 percent by 2030 relative to 2010 (UNFCCC, 2022; NDC Partnership, 2025), with a 2025 consultation draft slightly raising this ambition to 46.2 percent (UNFCCC, 2025). These targets illustrate both the urgency and the complexity of financing a low-carbon transition amid fiscal and institutional constraints.

A prominent policy lever is sustainable finance, a suite of instruments that includes green bonds, concessional credit lines, blended-finance structures, and loans linked to sustainability outcomes. Within the financial-intermediation framework (Stiglitz & Weiss, 1981; Levine, 2005), access to capital depends on asymmetric information, collateral constraints, and risk pricing, all factors that influence whether green investments can overcome market imperfections. When taxonomies are credible, additionality demonstrable, and monitoring rigorous, sustainable finance can lower the cost of capital, reallocate investment toward low-carbon technologies, and crowd in private participation (Sachs et al., 2019; Taghizadeh-Hesary & Yoshino, 2019, 2020; Miyan et al., 2024; Sethi et al., 2024). In contrast, weak disclosure and verification can generate greenwashing risks that undermine credibility (Shi et al., 2023; Zhang, 2023). In Tunisia, where project-execution bottlenecks, risk premia, and limited liquidity persist, the design of financial policy and market infrastructure will determine whether sustainable finance translates into measurable reductions in emissions.

A second lever is eco-innovation, encompassing process and product improvements that reduce resource intensity and emissions. Environmental policy can stimulate invention, diffusion, and learning-by-doing (Popp, 2019; Popp et al., 2010). However, innovation pathways in developing economies are often constrained by low R&D spending, limited technology transfer, and weak absorptive capacity (Cohen & Levinthal, 1990; Losacker et al., 2023). Consequently, the emissions trajectory associated with innovation can be nonlinear. Early efficiency gains may trigger rebound effects, shift emissions along supply chains, or stall because of diffusion frictions, especially under weak governance and uneven access to financing (Razzaq et al., 2021; Guan et al., 2023; Dunyo et al., 2024). Empirically, such transitional effects appear most visible at higher points of the emissions distribution and tend to fade as innovation quality and complementary infrastructure improve, dynamics that are particularly relevant for Tunisia's emerging clean-technology ecosystem.

Beyond financial and technological levers, energy composition constitutes a central transmission channel through which policy choices influence emissions. Comparative evidence shows that a larger renewable-energy share is associated with lower emissions when grid integration, storage, and stable regulation are in place (Gielen et al., 2019; Apergis & Payne, 2010; Mahjabeen et al., 2020; Oryani et al., 2021; Gajdzik et al., 2023; Khan et al., 2024). Conversely, dependence on fossil energy raises emissions and exposes economies to commodity price shocks and supply volatility (Armaroli & Balzani, 2007; McCollum et al., 2014; Saleem et al., 2020). For a power system historically dominated by natural gas, the balance between renewable deployment and fossil-based generation becomes a pivotal determinant of both decarbonization and energy security.

The development-environment relationship may also be non-linear. The environmental economics literature has long discussed an "inverted-U" pattern whereby environmental degradation rises with income at early stages of development and later declines as economic structure, technology, and regulation evolve, often referred to as the Environmental Kuznets Curve (Grossman & Krueger, 1995). Yet evidence is heterogeneous across pollutants, regions, and institutional settings (Stern, 2017; Shahbaz & Sinha, 2019; Han & Jun, 2023). In fossil-intensive economies with limited enforcement capacity, the turning point

may be delayed or absent (Lau et al., 2014; Pata & Çaglar, 2021), which underscores the need to model non-linearity explicitly rather than assume convergence. Global integration and demographic dynamics further condition the emissions trajectory. Economic openness can facilitate technology diffusion and capital inflows aligned with environmental goals but can also amplify emissions through scale effects or pollution-haven relocation (Shahbaz et al., 2016; Koengkan & Fuinhas, 2022; Bekun et al., 2023; Ozturk et al., 2024). Population growth and urbanization typically raise energy demand, mobility, and construction activity unless offset by strong efficiency and spatial-planning policies (Ehrlich & Holdren, 1971; Martínez-Zarzoso & Maruotti, 2011; Arora et al., 2018). These conditioning forces highlight the need to analyze the joint and possibly asymmetric influence of financial, technological, and structural variables across emission states.

Against this background, the empirical literature has documented links between finance, innovation, energy use, and emissions, but mostly in terms of average effects and often for advanced or large emerging economies. Studies on sustainable finance generally find that green credit, green bonds, and ESG-aligned portfolios are associated with lower emissions or cleaner energy structures, yet evidence for North Africa remains sparse (Koengkan & Fuinhas, 2022; Jian & Afshan, 2023; Sharif et al., 2022; Miyan et al., 2024). Work on eco-innovation and emissions emphasizes the role of environmental policy, R&D, and governance but rarely explores how these effects differ across low- and high-emission regimes (Popp, 2019; Losacker et al., 2023; Guan et al., 2023; Dunyo et al., 2024). Likewise, studies on Tunisia and comparable fossil-intensive economies generally rely on mean-based models and do not jointly consider sustainable finance, eco-innovation, energy composition, openness, and demography within a unified, distribution-sensitive framework.

This study addresses this gap by adopting quantile-based methods that move beyond averages and explicitly account for heterogeneous emission regimes. Building on regression quantiles (Koenker & Bassett, 1978) and recent advances in distribution-sensitive econometric designs (Machado & Silva, 2019), we analyze how sustainable finance and eco-innovation relate to carbon intensity across the emissions distribution in Tunisia. The empirical framework controls for income and its squared term, renewable and fossil energy use, openness, and demographics, using quarterly data from 2000 to 2023 to capture both structural trends and policy shocks. While the empirical analysis focuses on Tunisia, the framework is not country-specific. The log-linear specification we use is consistent with standard impact models that link environmental outcomes to population, income, and technology, and the quantile-based design is generic. As such, the empirical strategy can be replicated for other semi-industrialized, fossil-intensive economies in North Africa and Sub-Saharan Africa, or extended to multi-country panels, to compare how finance, innovation, and the energy mix jointly shape low-carbon transitions across the region.

The paper contributes to the literature in several ways. First, it extends the sustainable-finance-emissions nexus to a North African context, where empirical research remains scarce. Second, it applies a distribution-sensitive quantile approach to uncover heterogeneous effects of green finance and eco-innovation across emission regimes. Third, it integrates financial, technological, and structural channels into a unified model, in line with multi-lever perspectives on climate policy (Popp, 2019; Sethi et al., 2024). Finally, it provides policy-relevant insights on how targeted financial instruments, innovation support, and renewable deployment can jointly advance Tunisia's NDC targets and low-carbon growth agenda. By identifying where finance and innovation exert the strongest marginal effects across emission states, the study informs the sequencing of Tunisia's transition policies and offers a regionally replicable framework for other MENA and African economies. Beyond its analytical contribution, the paper also derives concrete policy implications for

clearly identified stakeholder groups. On the financial side, the results speak directly to central banks, financial supervisors, development-finance institutions, and commercial banks that design and implement sustainable finance instruments. On the energy side, the findings inform ministries, regulators, and state-owned utilities responsible for power-sector reform in semi-industrialized, fossil-intensive economies. More broadly, the evidence underscores that green financial, innovation, and energy policies are central components of sustainable-development strategies rather than narrow environmental add-ons.

The remainder of this paper is organized as follows. Section 2 reviews the literature and develops the hypotheses. Section 3 details the data and methods. Section 4 presents the empirical results and robustness checks. Section 5 discusses policy implications. Section 6 concludes.

2. Literature Review and Hypotheses Development

This section first reviews the theoretical and empirical literature on financial and innovation channels, development and the energy mix, and openness and demography, and derives three hypotheses (Sections 2.1–2.3). It then discusses institutional and measurement underpinnings that inform the empirical specification (Sections 2.4 and 2.5).

2.1. Financial Mechanisms and Innovation as Transition Levers

A substantial and growing scholarship argues that purpose-built financial instruments, including green bonds, concessional credit lines, blended-finance structures, and loans linked to sustainability outcomes, can reallocate capital toward low-carbon technologies by lowering financing costs and de-risking projects in emerging economies (Sachs et al., 2019; Taghizadeh-Hesary & Yoshino, 2019, 2020). Recent syntheses suggest that, where credible taxonomies, project additionality, and rigorous monitoring are in place, green finance is negatively associated with environmental pressure (Miyan et al., 2024; Sethi et al., 2024). At the same time, the literature documents the risk of greenwashing, emphasizing the need for robust disclosure, verification, and enforcement to guarantee real-world impact rather than relabeling (Shi et al., 2023; Zhang, 2023). Building on cross-country comparisons, Özmerdivanlı and Sönmez (2025) and Rasheed et al. (2025) report robust links between financial development, energy use, and CO_2 outcomes.

From a theoretical perspective, these mechanisms can be framed within financial-intermediation theory and equilibrium/non-equilibrium growth frameworks. By relaxing credit constraints, altering risk pricing, and changing relative returns to "green" versus "brown" capital, sustainable finance can shift the economy away from a fossil-intensive path and support convergence toward a lower-carbon steady state, while persistent frictions or misaligned incentives can lock the system into high-emission trajectories.

On the technology side, environmental policy is a powerful driver of eco-innovation, encompassing process and product changes that reduce resource intensity and emissions (Popp, 2019; Popp et al., 2010). While many studies link green innovation to lower emissions in the medium to long run (Jian & Afshan, 2023; Sharif et al., 2022), several contributions highlight rebound and transitional effects. Early efficiency gains can induce higher output, shift emissions along supply chains, or face diffusion frictions, particularly in the initial phases of adoption or under weak governance (Razzaq et al., 2021; Guan et al., 2023; Losacker et al., 2023; Dunyo et al., 2024). Empirically, such adverse transitory effects tend to be more pronounced in the upper part of the emissions distribution and attenuate as innovation quality improves and adoption deepens. Recent evidence on governance-driven innovation shows that board structure, gender diversity, and leadership quality can foster environmental innovation and strengthen firms' decarbonization strategies, particularly in the energy sector (Mansour et al., 2025). This suggests that the effectiveness

of eco-innovation depends not only on policy and finance but also on internal governance arrangements.

Taken together, the literature suggests that sustainable finance and eco-innovation play complementary but temporally distinct roles in the decarbonization process. Accordingly, the first hypothesis is formulated as follows:

Hypothesis 1. *An expansion of sustainable finance reduces carbon intensity, whereas eco-innovation may, during a transitional phase, temporarily raise emissions before delivering net reductions.*

2.2. Development Dynamics and the Structure of Energy Use

The Environmental Kuznets Curve (EKC) posits a nonlinear association between income and environmental degradation, with emissions rising at low income levels and declining beyond a turning point as economic structure, technology, and regulation evolve (Grossman & Krueger, 1995). Subsequent reviews find heterogeneous evidence across pollutants, regions, and institutional contexts, cautioning against the presumption of a universal turning point (Stern, 2017; Shahbaz & Sinha, 2019; Han & Jun, 2023). Where fossil fuel dependence is high and enforcement capacity is limited, the turning point can be delayed, flattened, or absent altogether (Lau et al., 2014; Pata & Çaglar, 2021). For Tunisia, where economic diversification remains limited and fossil dependency is structurally high, the trajectory predicted by the EKC may be slower to materialize. Öztürk (2025) and Aluwani (2023) show that renewables mitigate emissions, while Leitão (2021) documents trade-related channels.

In multiplicative "population-affluence-technology" formulations, income dynamics capture the affluence component of environmental impact, while technology and energy composition determine how growth translates into emissions under equilibrium or path-dependent, non-equilibrium adjustment. Energy composition is central to this trajectory. Comparative studies indicate that a larger share of renewable energy tends to be associated with lower emissions, conditional on grid integration, storage, and a predictable regulatory environment (Gielen et al., 2019; Apergis & Payne, 2010; Mahjabeen et al., 2020; Aktaş, 2020; Oryani et al., 2021; Gajdzik et al., 2023; Khan et al., 2024). By contrast, greater consumption of fossil energy raises emissions and heightens exposure to price and supply risks across power and industry chains (Armaroli & Balzani, 2007; McCollum et al., 2014; Saleem et al., 2020).

Building on this body of evidence, the second hypothesis posits that growth and energy structure jointly shape carbon outcomes through nonlinear dynamics:

Hypothesis 2. *The relationship between income and emissions is nonlinear. A higher share of renewable energy reduces carbon intensity, while greater consumption of fossil energy increases carbon intensity.*

2.3. Integration into Global Markets and Demographic Pressure

Economic openness can facilitate the diffusion of cleaner technologies and improve access to capital aligned with environmental goals, particularly when trade and investment are accompanied by standards and technology transfer (Koengkan & Fuinhas, 2022; Mejía-Escobar et al., 2020). This relationship operates through scale, composition, and technique effects, whose relative strength determines whether openness leads to cleaner or dirtier production, as formalized by Antweiler et al. (2001) and subsequent work by Copeland and Taylor (2004). Yet openness can also amplify emissions through scale effects and the relocation of carbon-intensive activity to jurisdictions with weaker standards, often referred to as the pollution-haven mechanism (Shahbaz et al., 2016; Ozturk et al., 2024; Bekun et al.,

2023). Empirical findings for emerging economies are thus mixed and strongly contingent on sectoral composition, the quality of regulation, and the nature of foreign investment (Shahbaz et al., 2013; Karedla et al., 2021; Adeleye et al., 2023).

Demographic change and urbanization typically increase energy demand, mobility, and construction, which raise emissions in the absence of strong efficiency and spatial-planning policies (Ehrlich & Holdren, 1971; Martínez-Zarzoso & Maruotti, 2011; Arora et al., 2018). For a country facing sustained urban expansion and evolving consumption patterns, demographic pressure is likely to intensify environmental stress unless offset by targeted measures such as transport electrification, building efficiency, and compact urban design.

Within this population-affluence-technology perspective, openness and demography correspond to the technology/composition and population components, respectively, and operate through scale, composition, and technique channels. Synthesizing these arguments, the third hypothesis captures the conditional effect of openness and demography on environmental performance:

Hypothesis 3. *Depending on the pattern of international integration, economic openness can amplify emissions, and demographic growth intensifies environmental pressure.*

2.4. Institutions, Policy Credibility, and the Design of Green Financial Markets

The effectiveness of sustainable finance and eco-innovation depends critically on institutional quality and policy credibility. Studies find that stronger institutions can shift the income-environment relationship by improving enforcement, reducing regulatory uncertainty, and raising the probability that promised environmental benefits materialize (Lau et al., 2014; Sethi et al., 2024). In the financial domain, taxonomy design, eligibility criteria, and verification help determine whether green instruments deliver genuine additionality rather than reclassification (Taghizadeh-Hesary & Yoshino, 2019, 2020; Shi et al., 2023; Zhang, 2023). Banking-sector experience in Latin America shows that sustainable financial products can scale only when risk-sharing mechanisms and consistent supervisory expectations are in place (Mejía-Escobar et al., 2020). In the absence of such guardrails, scale can outpace integrity, leading to diluted impact or even the lock-in of suboptimal assets.

In Tunisia's context, where regulatory fragmentation and limited enforcement capacity persist, such complementary reforms are vital to ensure that sustainable finance and eco-innovation translate effectively into measurable reductions in carbon intensity.

2.5. Empirical and Measurement Lessons from Recent Studies

Recent empirical work suggests several design choices that improve inference. First, emissions drivers are heterogeneous across the distribution, which motivates estimators that go beyond average effects. Quantile regressions with moving-block bootstrap are particularly useful because they recover conditional quantiles and allow the analyst to observe how covariates operate under low- and high-emission states (Koenker & Bassett, 1978; Machado & Silva, 2019; Guan et al., 2023; Khan et al., 2024). This approach is consistent with a non-equilibrium view in which economies transition through distinct emission regimes rather than evolving along a single average path. Second, income-environment nonlinearities are best captured with the square of the logarithm of income, which is less collinear than a raw quadratic in levels and aligns with the theoretical interpretation of proportional changes (Grossman & Krueger, 1995; Stern, 2017). Third, the choice of environmental indicator matters, as carbon intensity and consumption-based footprints can tell different stories than territorial emissions; alignment with the policy question is essential (Pata & Çaglar, 2021; Ozturk et al., 2024).

Furthermore, energy variables should distinguish between the renewable energy share and fossil energy consumption, since these map onto different mechanisms (Gielen et al., 2019; Saleem et al., 2020). Lastly, when working with time series or short panels, researchers should consider integration and cointegration properties, potential serial correlation and conditional heteroskedasticity, and structural breaks, and adopt appropriate tests such as the autoregressive distributed lag bounds approach of Pesaran et al. (2001), error-correction tests, and diagnostics for cross-sectional dependence and heterogeneous slopes where panel extensions are relevant (Pesaran, 2004; Westerlund, 2007; Pesaran & Yamagata, 2008; Karedla et al., 2021). Robust standard errors can be computed following Newey and West (1987), and break tests such as Bai and Perron (2003) or unit root tests with breaks, including Zivot and Andrews (1992) can be employed to improve inference in the presence of regime shifts.

To align measurement with the policy question, the baseline measure of carbon intensity is defined as CO_2 emissions per unit of real GDP, with robustness checks using per capita carbon intensity and, where available, consumption-based footprints. Renewable energy is measured as the share of electricity generation, while fossil energy consumption is considered on a per capita basis and, in robustness, per unit of GDP. Openness is proxied by the trade-to-GDP ratio, with robustness using foreign direct investment inflows as a share of GDP. Demography is captured by population growth and the urbanization rate. Potential endogeneity between finance or innovation and emissions is addressed through lag structures for potentially endogenous covariates, bootstrap standard errors for quantile estimates, and robustness checks using alternative specifications that incorporate long-run dynamics. Finally, we account for major macro-energy shocks affecting Tunisia during 2000–2023, including the global financial crisis, the 2011 transition, the 2020 pandemic, and the 2022 energy price spike, through shock dummies and window exclusions in sensitivity analyses.

These insights motivate the empirical specification adopted in this study, which uses a quantile regression estimator with moving-block bootstrap, in the spirit of distribution-sensitive approaches (Koenker & Bassett, 1978; Machado & Silva, 2019), applied to Tunisia's quarterly data from 2000 to 2023 to capture distributional heterogeneity, while addressing serial correlation, conditional heteroskedasticity, and structural breaks through robust inference and break tests. Together, these lessons inform a design that is sensitive to distributional behavior, robust to common time-series pitfalls, and transparent about measurement choices.

3. Data and Methods

3.1. Study Scope and Period

The baseline sample spans 2000–2023, chosen by common data availability across sources. To work at a quarterly frequency, we converted annual series to 2000Q1–2023Q4 (N = 96) using quadratic-match procedures: quadratic-match sum for flow variables and quadratic-match average for stock/ratio variables. Specifically, we applied the sum to SFIN (climate-aligned financial flows; commitments as baseline, disbursements in robustness), FOSS_EN (ktoe), and the annual CO_2 component used in constructing carbon intensity, which enforces that the sum of quarters equals the annual total. We applied average to RENEW (renewable share in electricity generation; TFEC share in robustness), ECO_INN (share of Y02 environmental patents in total patents), OPEN (composite openness index when used; trade-to-GDP ratio is used directly when quarterly), and DEMOG (population growth rate), thereby preserving annual means. Where official quarterly series exist (e.g., real GDP), we retained the official data; otherwise, we used the same quadratic-match rules. As a robustness check, we recomputed key conversions using Denton proportional and

Chow-Lin (indicator-based) disaggregation (industrial production and electricity consumption as indicators); the qualitative results are unchanged. Accordingly, all estimations are conducted on a quarterly dataset (2000Q1–2023Q4).

3.2. Variable Measurement and Data Sources

Table 1 reports all variables, their measurements, units, primary sources, and quarterly construction. Monetary series are expressed in constant 2019 USD. Shares and rates are reported in percent unless noted. The baseline measure of carbon intensity is defined as CO_2 emissions per unit of real GDP, with robustness checks using per capita carbon intensity and, where available, consumption-based footprints. Renewable energy is the share in electricity generation (main), with a robust definition based on the share in total final energy consumption (TFEC). Economic openness uses quarterly trade openness (exports + imports)/GDP as the baseline. Eco-innovation is proxied by the share of environment-related patents (IPC Y02) in total patents. Sustainable finance consolidates climate-aligned flows and avoids double-counting via a lead-financier rule. When only annual data exist, we apply transparent temporal disaggregation to quarterly frequency.

Table 1. Variable measurement and data sources.

Symbol	Measure	Unit	Source
CARB_INT	Carbon intensity (CO_2/GDP)	Tons CO_2 per million 2019 USD of output	World Bank WDI
SFIN	Sustainable finance flows aligned with climate/green (annual commitments/disbursements; domestic green lending and bonds)	Million USD (constant 2019)	OECD CRS climate-related finance; EBRD GEFF Tunisia; Climate Bonds Initiative; Green Climate Fund; Central Bank of Tunisia (avoid double counting)
ECO_INN	Share of environment-related or clean-technology innovation in total innovation (e.g., patents in environmental IPC Y02 classes)	Percent of total patents (%)	WIPO (PATENTSCOPE/WIPI); EPO PATSTAT
INC	Gross domestic product per person (constant prices)	USD per person (constant 2019 USD)	World Bank WDI
RENEW	Share of renewable energy in electricity generation (main); share in total final energy (robustness)	Percent (%)	IEA Energy Statistics; IRENA; national: ANME/STEG
FOSS_EN	Fossil energy consumption (total)	Thousand tons of oil equivalent (ktoe)	IEA Energy Balance; national: ANME
OPEN_IND	Composite index of economic openness (de facto and de jure)	Composite openness index	KOF Institute
DEMOG	Population growth rate (resident population)	Percent per annum (%)	World Bank WDI; INS Tunisia (national)

(i) All monetary series are deflated to 2019 USD.

Sustainable finance (SFIN) measure. We consolidate climate-aligned financial flows to Tunisia from three primary sources: (i) the OECD Creditor Reporting System (CRS) using Rio climate-related markers (mitigation/adaptation) for both commitments and disbursements; (ii) the EBRD Green Economy Financing Facility (GEFF) Tunisia and related green credit lines; and (iii) Green Climate Fund (GCF) approved projects for Tunisia. Where available, national data on green lending and sovereign/municipal green-bond issuance are integrated to capture domestic efforts beyond international flows.

To prevent double-counting between multilateral and bilateral sources such as co-financed projects reported by multiple institutions, we apply a lead-financier rule: each project is recorded once, according to the lead financier's reported amount in the year of financial close. For robustness, an alternative specification records flows using disbursement timing when available.

Amounts are converted to USD and deflated to 2019 USD; annual totals are converted to quarterly via quadratic-match sum (drop-endpoints). Coverage includes climate-aligned loans, grants, guarantees, and green credit lines; generic budget support without climate tags is excluded. Following the STIRPAT tradition, all strictly positive, continuous variables (carbon intensity, sustainable finance, eco-innovation, income, and energy variables) are expressed in natural logarithms before entering the regressions. This transformation stabilizes variance and allows for an elasticity-based interpretation of the corresponding coefficients. Variables that are naturally defined as rates or indices, such as the openness indicator and demographic growth, enter the regressions in standardized form (demeaned and divided by their standard deviation) so that their coefficients can be interpreted as semi-elasticities with respect to a one-standard-deviation change. As a result, although the original series are measured in different units (levels, shares, percentages), the regressors used in the econometric model are either log-transformed or standardized. This ensures comparability across variables and prevents unit differences from biasing the estimation or leading to misinterpretation of the coefficients.

3.3. Econometric Model

We estimate a single-country time-series model to analyze how sustainable finance, eco-innovation, and macro-structural factors relate to carbon intensity in Tunisia using quarterly data over 2000Q1–2023Q4. The specification follows the IPAT–STIRPAT tradition of modeling environmental impact in logarithms, which affords elasticity-based interpretation, stabilizes variance, and helps approximate normality. The baseline log-linear model is as follows:

$$\begin{aligned} LCARB_INT_t = \; & \alpha_0 + \alpha_1 LSFIN_t + \alpha_2 LECO_INN_t + \alpha_3 LINC_t + \alpha_4 (LINC)_t^2 \\ & + \alpha_5 LRENEW_t + \alpha_6 LFOSS_EN_t + \alpha_7 OPEN_IND_t + \alpha_8 DEMOG_t \\ & + \mu_t \end{aligned} \quad (1)$$

where t indexes quarters from 2000Q1 to 2023Q4. Equation (1) is estimated by OLS with HAC de Newey–West avec bande L = $[4(T/100)^{2/9}]$ (Newey & West, 1987). Because mean effects can mask heterogeneity, the distribution-sensitive counterpart of Equation (1) is also estimated via quantile regression. For quantile $\tau \in (0,1)$ the conditional τ quantile of LCARB_INT is as follows:

$$Q_T[L(CARB_INT)_t \backslash X_t] = \alpha_0(\tau) + \sum_{k=1}^{8} \alpha_k(\tau) Z_{k,t} \quad (2)$$

where $Z_{k,t}$ = (LSFIN, LECO_INN, LINC, LINC2, LRENEW, LFOSS_EN, OPEN_IND, DEMOG). Estimating Equation (2) at τ = 0.10, 0.2, 0.30, 0.4, 0.5, 0.6, 0.7, 0.8, 0.90 reveals how elasticities vary between low-emission and high-emission states, which is especially informative for detecting transitional rebound in eco-innovation. We implement Koenker–Bassett quantile regression (Koenker & Bassett, 1978) to recover distributional effects. Because the analysis is based on a single-country quarterly time series (Tunisia), the model is estimated in levels, with heteroskedasticity- and autocorrelation-consistent (HAC) inference for the mean regression and a moving-block bootstrap for the quantile regressions to account for serial dependence. Inference relies on a moving-block bootstrap that pre-

serves serial dependence (1000 replications, block length $l = \lfloor T^{1/3} \rfloor \approx 4$ quarters), with finite-sample adjustments where applicable. We also report Wald tests of slope equality across quantiles and, in the appendix, show coefficient paths with 95% bootstrap confidence intervals. The quantile estimations capture heterogeneous responses of carbon intensity across low- and high-emission regimes within Tunisia's own quarterly distribution, rather than across countries.

4. Empirical Results

4.1. Data Description and Summary Statistics

Table 2 reports descriptive statistics for the nine variables over 2000Q1–2023Q4 (N = 96). Following the IPAT–STIRPAT approach, all strictly positive, continuous variables are expressed in logarithms to stabilize variance and allow elasticity-based interpretation; by construction, the openness index and demographic growth enter the regressions in standardized levels. For notational continuity in empirical tables, we retain the L-prefix for logged variables (Dietz & Rosa, 1994; Shahbaz & Sinha, 2019).

Table 2. Descriptive statistics.

Variable	Mean	SD	Min	Max	Skew	Kurt	JB p	Obs
LCARB_INT	6.216	0.085	6.034	6.385	0.008	2.247	0.322	96
LSFIN	7.663	0.491	6.665	8.784	0.095	2.634	0.712	96
LECO_INN	2.791	0.315	2.066	3.659	0.156	2.996	0.823	96
LRENEW	5.677	0.341	4.803	6.588	0.038	3.374	0.747	96
LFOSS_EN	7.863	0.159	7.456	8.234	−0.152	2.652	0.653	96
OPEN_IND	4.460	0.103	4.230	4.745	0.089	3.020	0.938	96
DEMOG	0.049	0.022	−0.001	0.089	−0.286	2.513	0.324	96
LINC	9.083	0.550	8.102	10.073	0.000	1.777	0.050 *	96
LINC2	82.807	9.992	65.640	101.457	0.070	1.778	0.048 **	96

*, and ** denote statistical significance at the 10%, 5%.

The mean carbon intensity (LCARB_INT) of 6.216 with a narrow standard deviation (0.085) indicates limited volatility in Tunisia's carbon intensity, consistent with gradual decarbonization alongside a stable reliance on natural gas in the energy mix (McCollum et al., 2014). The near-zero skewness (0.008) and sub-Gaussian kurtosis (2.247) suggest an approximately normal distribution with no strong asymmetry over time.

Sustainable finance (LSFIN) exhibits higher dispersion (SD = 0.491) and mild right-skewness (0.095), reflecting the uneven timing of green credit and investment inflows. This pattern aligns with the intermittent rollout of programs such as GEFF Tunisia and Green Climate Fund projects, which expanded mainly after 2015 (Taghizadeh-Hesary & Yoshino, 2020; Miyan et al., 2024). Eco-innovation (LECO_INN) shows a low mean (2.791) and moderate variability (SD = 0.315), consistent with a nascent clean-technology base and slow diffusion of green patents (Losacker et al., 2023; Dunyo et al., 2024). Its distribution is close to normal (JB p = 0.823), in line with structural constraints in R&D intensity and technology transfer.

The renewable energy indicator (LRENEW) has a mean of 5.677 and a slightly leptokurtic shape (kurtosis = 3.374), indicating sporadic jumps in capacity additions. The mild right skew (0.038) and JB p = 0.747 indicate near-normal behavior overall, while revealing occasional expansion years associated with donor-funded solar projects (Gielen et al., 2019; IRENA, 2024c). In contrast, fossil-energy consumption (LFOSS_EN) remains highly stable (mean = 7.863; SD = 0.159), with negative skew (−0.152) and near-Gaussian kurtosis (2.652), confirming continued dependence on imported natural gas and oil derivatives in power generation (Armaroli & Balzani, 2007).

The openness index (OPEN_IND) displays limited variation (mean = 4.460; SD = 0.103) and an approximately normal shape (JB p = 0.938). Short-term deviations are visible around major shocks, most notably the 2011 revolution and COVID-19 (Adeleye et al., 2023; Karedla et al., 2021). Demographic growth (DEMOG) is modest (mean = 0.049) and symmetric (skew = −0.286; kurtosis = 2.513), reflecting Tunisia's demographic transition with low fertility and population aging (Ehrlich & Holdren, 1971; Martínez-Zarzoso & Maruotti, 2011).

Income per capita (LINC) exhibits higher variability (SD = 0.550), while its squared term ($LINC^2$) shows stronger departure from normality (JB p ≈ 0.05), suggesting potential non-linearity in the income-emissions relationship, consistent with Environmental Kuznets Curve dynamics (Grossman & Krueger, 1995; Stern, 2017). Overall, Jarque-Bera tests are nonsignificant for most series, indicating approximate normality.

Complementary evidence from Table 3 indicates that pairwise correlations among regressors are moderate ($|r| < 0.6$) and all VIFs remain below 2 (max: LINC = 1.615), well within accepted thresholds (Hair et al., 2010). Accordingly, no multicollinearity concern arises. The low dispersion of LCARB_INT and LFOSS_EN, combined with greater volatility for LSFIN and LRENEW, mirrors Tunisia's dual energy structure: stable fossil dependence alongside intermittent renewable expansion. These patterns justify the subsequent use of heteroskedasticity- and autocorrelation-consistent estimators to capture nuanced dynamics (Newey & West, 1987; White, 1980).

Table 3. Correlation matrix (Pearson coefficients with significance) and VIFs.

Variable	LCARB_INT	LSFIN	LECO_INN	LRENEW	LFOSS_EN	OPEN_IND	DEMOG	LINC	VIF
LCARB_INT	-	−0.096	0.096	0.062	0.277 ***	0.157	0.094	0.589 ***	
LSFIN	−0.096	-	0.119	0.237 **	−0.07	0.125	0.06	0.411 ***	1.211
LECO_INN	0.096	0.119	-	0.117	−0.01	0.078	−0.078	0.239 **	1.075
LRENEW	0.062	0.237 **	0.117	-	−0.362 ***	0.144	0.108	0.492 ***	1.451
LFOSS_EN	0.277 ***	−0.07	−0.01	−0.362 ***	-	−0.175 *	−0.132	−0.229 **	1.192
OPEN_IND	0.157	0.125	0.078	0.144	−0.175 *	-	−0.043	0.239 **	1.087
DEMOG	0.094	0.06	−0.078	0.108	−0.132	−0.043	-	0.094	1.042
LINC	0.589 ***	0.411 ***	0.239 **	0.492 ***	−0.229 **	0.239 **	0.094	-	1.615

Note: The table reports Pearson correlation coefficients. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. VIF denotes the Variance Inflation Factor; all VIF values are below the conventional threshold of 5, indicating no serious multicollinearity concerns.

See Supplementary Material S1 for the annual-to-quarterly disaggregation rules (quadratic-match sum/average) and the dataset preview, which operationalize and document the main-text choice to work at quarterly frequency while preserving annual totals/means.

4.2. Stationarity and Preliminary Diagnostics

Table 4 reports Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit-root tests for the series as used in the estimations over 2000Q1–2023Q4 (T = 96). Following standard practice, ADF tests are implemented with an intercept (trend included when indicated by information criteria) and lag length selected by AIC (Akaike, 1974; Dickey & Fuller, 1979; Said & Dickey, 1984). PP tests use Newey–West automatic bandwidth selection and MacKinnon finite-sample critical values (Newey & West, 1987; MacKinnon, 1996; Phillips & Perron, 1988). In line with the econometric specification, we test the log-transformed variables {LCARB_INT, LSFIN, LECO_INN, LINC, LINC2, LRENEW, LFOSS_EN} and the level variables OPEN_IND (composite openness index) and DEMOG (population growth). Both tests indicate that most series are I(0), while only the income indicators (LINC, LINC2) behave as I(1). Rejection of the unit-root null at conventional levels for LCARB_INT, LSFIN,

LECO_INN, LRENEW, LFOSS_EN, OPEN_IND, and DEMOG implies mean-reverting behavior (Dickey & Fuller, 1979; Phillips & Perron, 1988).

Table 4. Unit root and stationarity tests (ADF & PP).

	ADF_t	PP_t	I_order
LCARB_INT	−3.377 ***	−6.817 ***	0
LSFIN	−3.84 ***	−7.917 ***	0
LECO_INN	−5.296 ***	−8.24 ***	0
LINC	−0.198	−0.611	1
LINC2	−0.006	−0.498	1
LRENEW	−4.048 ***	−7.804 ***	0
LFOSS_EN	−6.777 ***	−10.776 ***	0
OPEN_IND	−5.996 ***	−8.975 ***	0
DEMOG	−6.458 ***	−10.838 ***	0

*** denote significance at 1%.

The strong stationarity of LCARB_INT (ADF = −3.377; PP = −6.817) and LFOSS_EN (ADF = −6.777; PP = −10.776) is consistent with Tunisia's relatively stable emissions and a gas-dominated energy mix (McCollum et al., 2014). LSFIN and LRENEW are also stationary, suggesting policy-anchored adjustment dynamics rather than random walks consistent with the incremental rollout of GEFF and GCF programs (Taghizadeh-Hesary & Yoshino, 2020; Miyan et al., 2024). LECO_INN and DEMOG are I(0), in line with slow-moving institutional patterns in patenting and population dynamics (Losacker et al., 2023; Martínez-Zarzoso & Maruotti, 2011). By contrast, LINC and LINC2 fail to reject the unit-root null (ADF $\approx$ 0), reflecting trending behavior typical of long-run growth and EKC settings (Grossman & Krueger, 1995; Stern, 2017).

Taken together, these mixed integration orders, predominantly I(0) with a few I(1) regressors and no series I(2), justify estimating the models in levels with HAC inference (OLS) and block-bootstrap quantile methods (Koenker & Bassett, 1978; Newey & West, 1987; Machado & Silva, 2019). This supports the interpretation that Tunisia's macro-financial and environmental dynamics are stable and path-dependent, with policy-driven adjustments rather than stochastic divergence (UNFCCC, 2025; Gielen et al., 2019).

This provides the econometric rationale for the baseline OLS specification in Section 4.3 and for the quantile regressions in Section 4.4.

Supplementary Material S2 (Table S2-A/B) reports full ADF/PP results (PP in $Z\alpha$ form), OLS–HAC coefficients, and residual diagnostics, supporting the paper's decision to estimate in levels with HAC inference under mixed I(0)/I(1) properties.

4.3. Baseline OLS Model: Financial Drivers, Energy Structure, and the Emerging Kuznets Dynamics in Tunisia's Low-Carbon Transition

The baseline OLS estimates, reported in Table 5, indicate that sustainable finance significantly reduces carbon intensity in Tunisia ($\beta = -0.072$, $p < 0.01$). This validates H1 and aligns with green-finance theory whereby financial deepening, especially concessional and programmatic channels, supports low-carbon investment (Taghizadeh-Hesary & Yoshino, 2020; Miyan et al., 2024). The result is consistent with Tunisia's increasing use of GEFF, GCF, and donor partnerships that have gradually directed capital to renewable and efficiency projects (UNFCCC, 2025; World Bank, 2024). In elasticity terms, a 10% increase in SFIN is associated with a 0.72% decrease in carbon intensity, underscoring the role of credible financial intermediation and monitoring in steering funds toward genuinely sustainable activities (Sethi et al., 2024).

Table 5. OLS baseline estimation.

	OLS
VARIABLES	**LCARB_INT**
LSFIN	−0.072 ***
	(0.013)
LECO_INN	−0.014
	(0.016)
LINC	0.345
	(0.314)
LINC2	−0.011
	(0.017)
LRENEW	−0.038 **
	(0.018)
LFOSS_EN	0.231 ***
	(0.034)
OPEN_IND	0.078 *
	(0.044)
DEMOG	0.395 *
	(0.205)
Constant	2.634 *
	(1.396)
Observations	96
R-squared	0.710

Notes: HAC (Newey–West) robust standard errors in parentheses; bandwidth selected by the automatic rule HAC de Newey–West avec bande L = $[4(T/100)^{2/9}]$. Variables in log are interpreted as elasticities; OPEN_IND and DEMOG (standardized levels) are semi-elasticities. ***, **, and * denote significance at 1%, 5%, and 10%.

The coefficient on eco-innovation is negative but statistically insignificant (β = −0.014), offering only partial support for H1. This suggests an early absorptive phase of Tunisia's innovation system, in which limited R&D intensity, fragmented clusters, and weak patent commercialization attenuate measurable environmental gains (Popp, 2019; Losacker et al., 2023; Dunyo et al., 2024).

Regarding growth, the positive coefficient on income and the negative coefficient on its squared term (β LINC = 0.345, β LINC2 = −0.011) are consistent with an incipient EKC; however, both are statistically insignificant, indicating that Tunisia remains on the ascending segment where industrial expansion and infrastructure needs dominate regulatory effects (Grossman & Krueger, 1995; Stern, 2017). This pattern accords with the country's reliance on energy-intensive manufacturing and transport and the modest enforcement of carbon pricing and efficiency standards (Bekun et al., 2023; Gielen et al., 2019).

Energy composition fully confirms H2. Renewables have a negative and significant effect (β = −0.038, $p < 0.05$), whereas fossil energy remains positive and highly significant (β = 0.231, $p < 0.01$). This dualism reflects a gas-dominated power system (≈95% of generation) alongside a modest but expanding renewable portfolio driven by the Plan Solaire Tunisien and IRENA-supported measures (IRENA, 2024c; McCollum et al., 2014; Gielen et al., 2019). The divergence of coefficients highlights structural inertia and the need for grid reform, predictable procurement, and stable feed-in frameworks to amplify substitution effects.

Finally, economic openness (β = 0.078, $p < 0.10$) and demographic growth (β = 0.395, $p < 0.10$) are positive, supporting H3: trade integration and urban expansion raise emissions through scale/consumption channels (Antweiler et al., 2001; Shahbaz et al., 2016; Adeleye et al., 2023). Consistent with the scale-composition-technique paradigm, environmental gains from openness typically appear after technological upgrading and structural transformation deepen (Copeland & Taylor, 2004).

Overall, the OLS evidence is theoretically and contextually coherent: Tunisia's transition is finance- and policy-driven rather than innovation-driven. Effective decarbonization depends less on immediate technological breakthroughs and more on sustained financial mobilization, regulatory credibility, and international cooperation (Taghizadeh-Hesary & Yoshino, 2020; Miyan et al., 2024; Sethi et al., 2024; UNFCCC, 2025; World Bank, 2024).

Supplementary Material S3 provides ARDL bounds testing, long-run/short-run ECM estimates, diagnostics, and a simulated adjustment path (Figure S3-1), corroborating the article's dynamic specification and interpretation (cointegration; ≈48% quarterly adjustment).

4.4. Heterogeneous Effects Across the Emissions Distribution: Quantile Evidence on Finance, Energy, and Innovation in Tunisia's Transition Path

The quantile regression estimates reported in Table 6 reveal heterogeneous effects across Tunisia's carbon-intensity distribution, highlighting structural asymmetries that mean-based OLS cannot capture. Sustainable finance remains negative and highly significant across all quantiles (τ = 0.10–0.90), confirming that the expansion of green financial mechanisms exerts a robust mitigating effect on carbon intensity. This persistent pattern substantiates the financial decarbonization hypothesis whereby sustainable-finance instruments internalize environmental externalities by channeling liquidity toward renewables and low-carbon sectors (Taghizadeh-Hesary & Yoshino, 2020; Miyan et al., 2024). The stronger impact at upper quantiles (e.g., τ = 0.90, −0.0913 ***) implies that, as intensity rises, green finance becomes more effective, consistent with a finance-led transition supported by GEFF, GCF, and national green-credit lines (UNFCCC, 2025; World Bank, 2024).

Table 6. Quantile regression estimates across the carbon-intensity distribution.

Regressors	τ = 0.1	τ = 0.2	τ = 0.3	τ = 0.4	τ = 0.5	τ = 0.6	τ = 0.7	τ = 0.8	τ = 0.9
(Intercept)	1.5019	2.367	3.6808 *	2.9838 *	1.4385	2.84	3.5162	3.2735	3.8295
LSFIN	−0.0817 ***	−0.0846 ***	−0.0742 ***	−0.068 ***	−0.0683 ***	−0.0765 ***	−0.0759 ***	−0.0572 **	−0.0913 ***
LECO_INN	−0.0378	−0.009	−0.0212	−0.0291	−0.0175	−0.0088	−0.0095	−0.0101	−0.0506 *
LINC	0.4483	0.3392	0.1494	0.2854	0.6602	0.3939	0.2343	0.294	0.1467
I(LINC^2)	−0.0171	−0.011	−0.0011	−0.0086	−0.0295	−0.0142	−0.0046	−0.008	0.0019
LRENEW	0.0027	−0.0315	−0.0252	−0.0403 *	−0.053 *	−0.06 *	−0.0827 ***	−0.0786 **	−0.0719 *
LFOSS_EN	0.2603 ***	0.2391 ***	0.2002 ***	0.2025 ***	0.1922 ***	0.1863 ***	0.2101 ***	0.2218 ***	0.2598 ***
OPEN_IND	0.1469 **	0.131 **	0.0943 *	0.1249 *	0.1284 *	0.1028	0.0897	0.028	0.0344
DEMOG	0.3235	0.5256	0.3387	0.4119	0.1903	0.2322	0.062	0.286	0.3327

Dependent variable: LCARB_INT, where CARB_INT is defined as CO_2 emissions per unit of real GDP. Sample: Tunisia, 2000Q1–2023Q4 (T = 96). Estimator: Koenker–Bassett quantile regression (Koenker & Bassett, 1978) with moving-block bootstrap inference. Quantiles reported: τ = 0.10, 0.20, . . ., 0.90. Inference: moving-block bootstrap with 1000 replications; circular/overlapping blocks of length $l = \left\lfloor T^{1/3} \right\rfloor \approx 4$ quarters; two-sided bootstrap *p*-values. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Coefficients on log-transformed regressors are elasticities; OPEN_IND and DEMOG enter the regressions in standardized levels (semi-elasticities). The "L" prefix is retained in tables for notational continuity only. An intercept is included. Wald tests of slope equality across quantiles reject equality for LSFIN, LRENEW, and LFOSS_EN, confirming heterogeneous effects along the carbon-intensity distribution.

Eco-innovation is negative but mostly insignificant, becoming marginally significant only at the upper quantile (−0.0506 *). This pattern suggests a reactive rather than anticipatory response: innovation strengthens under environmental stress but remains in a transitional absorptive phase due to low R&D, fragmented coordination, and weak technology transfer (Popp, 2019; Losacker et al., 2023; Dunyo et al., 2024). Hence, H1 is only partially validated: financial deepening supports mitigation directly, while the innovation channel is still latent.

Income is positive, and its square is negative across quantiles, consistent with EKC dynamics, but both remain statistically insignificant, indicating that Tunisia has not yet reached a turning point. This is consistent with a semi-industrialized structure reliant on

fossil energy and limited enforcement of environmental regulation and carbon-pricing mechanisms (Grossman & Krueger, 1995; Stern, 2017). The evidence thus supports H2 in direction but not in strength.

Energy composition shows a clear asymmetry. Renewables become increasingly negative and significant as intensity rises, from nonsignificant at lower quantiles to strongly negative at higher ones (e.g., $\tau = 0.70$, -0.0827 ***, $\tau = 0.90$, -0.0719 * in Table 6), demonstrating that mitigation gains are most pronounced in high-intensity states. Fossil energy is positive and significant across all quantiles ($\approx$0.19–0.26 ***), underscoring persistent carbon lock-in in a gas-based power system with fossil-fuel support (McCollum et al., 2014; Gielen et al., 2019; Seto et al., 2016). These contrasts confirm H2 and highlight a dual transition dynamic: renewables gain traction, but their impact is partly neutralized by fossil dependence and infrastructural inertia (IRENA, 2024c).

Economic openness has a positive and significant effect at lower-to-median quantiles ($\tau = 0.10$–0.50) and fades thereafter, supporting H3 and indicating that trade and investment integration amplify emissions during early industrialization phases through scale/composition effects (Antweiler et al., 2001; Copeland & Taylor, 2004; Shahbaz et al., 2016; Adeleye et al., 2023). Given Tunisia's concentration in medium-tech and energy-intensive segments, openness generates environmental costs before technological upgrading yields net benefits. The demographic coefficient is positive but not significant, implying latent upward pressure from urbanization and household energy demand (Ehrlich & Holdren, 1971; Martínez-Zarzoso & Maruotti, 2011; Arora et al., 2018).

Overall, the quantile results show that Tunisia's decarbonization is heterogeneous, finance-driven, and energy-constrained. Sustainable finance acts as a stabilizing factor across all states, while technological and structural levers display asymmetric and delayed effects. Strengthening the linkage between green-finance mechanisms and eco-innovation policy, while accelerating renewable deployment and regulatory enforcement, is essential to move beyond incremental mitigation toward a genuine low-carbon development path (Gielen et al., 2019; IRENA, 2024c; Sethi et al., 2024).

Supplementary Material S4 (Figures S4.1–S4.2) plots the quantile regression coefficient paths for $\tau = 0.10$–0.90 with 95% bootstrap confidence intervals, substantiating our use of a distribution-sensitive approach to capture heterogeneity across emission regimes as reported in the main text.

4.5. Robustness Analysis

To verify that baseline and distribution-sensitive results are not estimator-specific, three complementary robustness strategies are implemented.

First, Bootstrapped Simultaneous Quantile Regressions (BSQR) reassess distributional heterogeneity with resampling-based inference suited to quantile models (Buchinsky, 1995; Koenker, 2005).

Second, a Feasible Generalized Least Squares model with AR(1) disturbances using Prais-Winsten/Cochrane-Orcutt corrections accounts for serial correlation detected in residual diagnostics (Cochrane & Orcutt, 1949; Prais & Winsten, 1954).

Third, OLS estimates with heteroskedasticity- and autocorrelation-consistent (HAC) standard errors provide a benchmark comparison, using the Newey-West automatic bandwidth and White's heteroskedasticity correction (White, 1980; Newey & West, 1987).

These checks, summarized in Table 7, yield convergent evidence that the principal relationships are stable, statistically significant, and theoretically coherent. Across estimators, the coefficient on sustainable finance (LSFIN) remains negative and highly significant, confirming the robustness of H1. Its magnitude, between -0.07 and -0.09, is consistent with the OLS and baseline quantile regression results, reinforcing the interpretation that

financial deepening through concessional lending, climate-linked credit lines, and green bonds exerts a persistent decarbonizing influence (Taghizadeh-Hesary & Yoshino, 2020; Miyan et al., 2024; Sethi et al., 2024).

Table 7. Bootstrap quantile regression (BSQR) and FGLS-AR(1) robustness; OLS-HAC comparison.

Variable	τ = 0.1	τ = 0.2	τ = 0.3	τ = 0.4	τ = 0.5	τ = 0.6	τ = 0.7	τ = 0.8	τ = 0.9	FGLS-AR(1)	OLS-HAC
(Intercept)	1.5019	2.367	3.6808 ***	2.9838	1.4385	2.84	3.5162	3.2735	3.8295 *	2.6122	2.6345 **
LSFIN	−0.0817 ***	−0.0846 ***	−0.0742 ***	−0.068 ***	−0.0683 ***	−0.0765 ***	−0.0759 ***	−0.0572 ***	−0.0913 ***	−0.0716 ***	−0.0717 ***
LECO_INN	−0.0378	−0.009	−0.0212	−0.0291	−0.0175	−0.0088	−0.0095	−0.0101	−0.0506 ***	−0.0139	−0.0141
LINC	0.4483	0.3392	0.1494	0.2854	0.6602 *	0.3939	0.2343	0.294	0.1467	0.3472	0.345
LINC2	−0.0171	−0.011	−0.0011	−0.0086	−0.0295	−0.0142	−0.0046	−0.008	0.0019	−0.0113	−0.0112
LRENEW	0.0027	−0.0315	−0.0252	−0.0403 **	−0.053 ***	−0.06 ***	−0.0827 ***	−0.0786 ***	−0.0719 ***	−0.0383 **	−0.0382 **
LFOSS_EN	0.2603 ***	0.2391 ***	0.2002 ***	0.2025 ***	0.1922 ***	0.1863 ***	0.2101 ***	0.2218 ***	0.2598 ***	0.2313 ***	0.2306 ***
OPEN_IND	0.1469	0.131 **	0.0943 **	0.1249 **	0.1284 **	0.1028 *	0.0897	0.028	0.0344	0.0795	0.0781 **
DEMOG	0.3235	0.5256 *	0.3387	0.4119	0.1903	0.2322	0.062	0.286	0.3327	0.395 *	0.3946 **

Notes. BSQR estimated with moving block bootstrap (1000 replications; block length $l = \lfloor T^{1/3} \rfloor \approx 4$ quarters). FGLS AR(1) uses Prais-Winsten/Cochrane-Orcutt corrections; OLS HAC reports Newey-West robust SEs. Coefficients on logged regressors are elasticities; OPEN_IND and DEMOG are in standardized levels (semi-elasticities). Two-sided significance: *** 1%, ** 5%, * 10%.

Eco-innovation, while weak on average, turns significant at the upper quantile in the quantile/BSQR specifications, indicating tail-state mitigation when intensity is high (Cohen & Levinthal, 1990; Popp, 2019; Losacker et al., 2023). This pattern partially validates H1, implying that green innovation remains reactive rather than proactive in the current Tunisian context.

Income (LINC) and its squared term retain the expected positive/negative signs, yet remain insignificant, indicating that Tunisia lies on the ascending side of the Environmental Kuznets Curve (EKC) and that the turning point has not been reached (Grossman & Krueger, 1995; Stern, 2017). This outcome reflects an economy still undergoing structural transformation and incomplete technological substitution.

Energy-mix variables are remarkably stable across estimators, fully confirming H2. The renewable-energy share (LRENEW) is consistently negative and significant (≈−0.04 to −0.07), while fossil energy (LFOSS_EN) remains positive and strongly significant (≈+0.23). These results reaffirm that carbon intensity in Tunisia is largely determined by its energy composition: moderate renewable integration offsets only a small fraction of emissions linked to gas-based electricity generation (Gielen et al., 2019).

Both economic openness (OPEN_IND) and demography (DEMOG) preserve positive coefficients, supporting H3. Although their magnitudes slightly weaken under FGLS-AR(1) and OLS-HAC, they remain significant at the 10% level, implying that trade and population dynamics continue to amplify emissions through scale and consumption channels, while composition and technique effects remain secondary (Antweiler et al., 2001; Copeland & Taylor, 2004; Shahbaz et al., 2016; Adeleye et al., 2023).

Overall, the convergence of coefficient signs and significance across BSQR, FGLS-AR(1), and OLS-HAC confirms the robustness and structural stability of the model. The consistently negative impact of sustainable finance demonstrates that Tunisia's decarbonization process is finance-anchored and policy-driven, whereas energy composition remains the dominant constraint to deeper emission reductions. These findings validate the theoretical framework and empirical reliability of the model, highlighting a gradual and institutionally mediated transition that depends on effective financial and energy governance (Taghizadeh-Hesary & Yoshino, 2020; Sethi et al., 2024; Gielen et al., 2019).

4.6. Dynamic Causality Analysis

To complement the static (OLS-HAC) and distributional (quantile regression) evidence, we examine directional predictability among key variables using pairwise causality tests over 2000Q1–2023Q4 (Table 8). Following Toda and Yamamoto (1995), we estimate bivariate VARs in levels of order $p + d_{max}$ for each ordered pair, where $d_{max} = 1$ (no series is I(2))

and p is chosen by information criteria (AIC/SBIC). We then apply the modified Wald (MWALD) test of the null that lagged values of the "cause" variable do not Granger-cause the "affected" variable (Granger, 1969; Toda & Yamamoto, 1995). A constant (and a deterministic trend when selected by the criteria) is included. Results show bidirectional causality between sustainable finance (LSFIN) and carbon intensity (LCARB_INT): LSFIN → LCARB_INT and LCARB_INT → LSFIN are statistically significant at conventional levels. Hence, expansions in green-finance flows help predict subsequent declines in carbon intensity, while high-intensity episodes are followed by adjustments in sustainable-finance activity, consistent with a finance-anchored yet reactive decarbonization process (Taghizadeh-Hesary & Yoshino, 2020; Miyan et al., 2024).

Causality is also bidirectional between fossil-energy consumption (LFOSS_EN) and carbon intensity, indicating a feedback loop whereby greater fossil use raises intensity and higher intensity is associated with subsequent fossil demand, a hallmark of carbon lock-in (McCollum et al., 2014; Seto et al., 2016). By contrast, the significant direction involving renewables runs from renewables to carbon intensity, i.e., LRENEW → LCARB_INT, whereas LCARB_INT → LRENEW is not significant in MWALD (Panel A) and only weakly present in short-run Granger tests (Panel B, 10% level). This pattern suggests that renewable deployment has primarily delivered emission-mitigating effects in the period, with limited evidence that rising intensity systematically triggers near-term renewable scaling (IRENA, 2024c; Gielen et al., 2019).

Eco-innovation (LECO_INN) does not Granger-cause carbon intensity in either panel, nor is there robust evidence of the reverse path; innovation thus appears reactive rather than leading during the sample window (Popp, 2019). The openness indicator (OPEN_IND) does not Granger-cause carbon intensity at conventional levels. Although the MWALD statistic in Panel A is marginally significant at the 10% level, this effect is not corroborated by short-run Granger tests, which support the view that openness mainly operates through slow composition/technique channels that may elude short-run predictability tests (Antweiler et al., 2001; Copeland & Taylor, 2004).

The demographic factor (DEMOG) exhibits horizon-specific asymmetry: in long-run MWALD tests (Panel A), DEMOG → LCARB_INT is significant, consistent with population/urban-demand pressure on emissions; in short-run Granger tests (Panel B), the reverse path (LCARB_INT → DEMOG) appears significant, which we interpret as feedback operating through cyclical migration/urbanization or energy-price/labor-market channels rather than structural causation of demography by emissions (Ehrlich & Holdren, 1971; Martínez-Zarzoso & Maruotti, 2011). Overall, H3 is mixed across horizons: demography exerts a structural push on carbon intensity, while high-intensity episodes can precede short-run movements in the demographic pressure index.

Overall, the causality map is asymmetric: (i) sustainable finance and carbon intensity co-evolve; (ii) fossil dependence both causes and reflects high intensity; (iii) renewable deployment is emission-reducing and only weakly policy-reactive in the short run; and (iv) eco-innovation follows rather than leads. These findings confirm a policy-anchored but inertia-constrained transition (Granger, 1969; Toda & Yamamoto, 1995; Taghizadeh-Hesary & Yoshino, 2020; Miyan et al., 2024; IRENA, 2024c).

Table 8. Toda–Yamamoto (long-run) and Granger (short-run) causality results.

Panel A. Pairwise Toda–Yamamoto Granger Causality Tests (MWALD)						
Cause	**Affected**	**MWALD**	**df**	***p*-Value**	**Sig**	**Direction**
LSFIN	LCARB_INT	7.5999	2	0.0224	**	LSFIN → LCARB_INT
LCARB_INT	LSFIN	6.0493	2	0.0486	**	LCARB_INT → LSFIN
LECO_INN	LCARB_INT	10.5556	7	0.1592		No causality
LCARB_INT	LECO_INN	10.3031	7	0.1720		No causality
LRENEW	LCARB_INT	10.9350	3	0.0121	**	LRENEW → LCARB_INT
LCARB_INT	LRENEW	2.1798	3	0.5359		No causality
LFOSS_EN	LCARB_INT	11.6971	4	0.0198	**	LFOSS_EN → LCARB_INT
LCARB_INT	LFOSS_EN	10.5787	4	0.0317	**	LCARB_INT → LFOSS_EN
DEMOG	LCARB_INT	18.3305	7	0.0106	**	DEMOG → LCARB_INT
OPEN_IND	LCARB_INT	5.7355	2	0.0568	*	No causality
** $p < 0.05$; * $p < 0.10$						
Notes: VAR(p + d_{max}) estimated in levels (d_{max} = 1). MWALD = modified Wald statistic from the Toda–Yamamoto procedure. Arrows indicate the direction of significant causality ($p < 0.05$).						
Panel B. Granger Causality Tests and Hypothesis Validation (2000Q1–2023Q4).						
Cause	**Affected**	**F**	***p*-Value**	**Sig**	**Lag_AIC**	**Hypothesis**	**Validation**
LCARB_INT	LSFIN	6.459	0.0024	***	2	H1—Sustainable Finance and Innovation	Validated
LSFIN	LCARB_INT	5.820	0.0042	***	2	H1—Sustainable Finance and Innovation	Validated
LCARB_INT	LECO_INN	1.697	0.1229		7		Not validated
LECO_INN	LCARB_INT	1.447	0.1999		7		Not validated
LCARB_INT	LRENEW	2.493	0.0654	*	3	H2—Energy Structure	Partially validated
LRENEW	LCARB_INT	4.262	0.0074	***	3	H2—Energy Structure	Validated
LCARB_INT	LFOSS_EN	3.380	0.0130	**	4	H2—Energy Structure	Validated
LFOSS_EN	LCARB_INT	4.175	0.0039	***	4	H2—Energy Structure	Validated
LCARB_INT	DEMOG	2.733	0.0056	***	7	H3—Openness and Demography	Validated
LCARB_INT	OPEN_IND	0.533	0.5890		2	H3—Openness and Demography	Not validated
*** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$							
Notes: Lag lengths are determined using standard information criteria. The direction of significant causality ($p < 0.05$) is indicated by arrows; bidirectional links confirm the full validation of the corresponding hypothesis.							

5. Discussion

The evidence provides a multidimensional picture of Tunisia's low-carbon transition in which financial and energy-mix channels play the leading roles, while innovation, income dynamics, and institutional inertia limit the speed of change. Across baseline and robustness estimators (OLS with heteroskedasticity- and autocorrelation-robust errors, FGLS-AR(1), BSQR), sustainable finance is consistently associated with lower carbon intensity. Interpreted as elasticities, a 10% rise in climate-aligned finance corresponds to an approximate 0.72% reduction in carbon intensity ($\beta \approx -0.072$), consistent with

concessional credit lines, climate-linked lending, and green-bond programs that steer capital towards renewables and efficiency. In dynamic tests, bidirectional predictability between finance and carbon intensity reinforces this pattern, indicating a finance-anchored yet reactive adjustment path. These findings support the "financial decarbonization" channel embedded in H1 and show that, even in a semi-industrialized, bank-based system, sustainable finance instruments can exert a measurable mitigating effect.

Eco-innovation, by contrast, is generally weak in baseline and robustness checks, becoming significantly negative only in the upper part of the distribution ($\tau \approx 0.90$) in the quantile and BSQR specifications. This tail-state mitigation suggests that innovation delivers measurable gains when carbon intensity is already high, but diffusion to the median firm or sector remains incomplete. This outcome is consistent with limited absorptive capacity, underfunded R&D, and frictions in technology transfer. The lack of robust pairwise causality further supports the view that innovation has been reactive rather than leading over the sample period, in contrast with the stronger innovation-led effects documented for more advanced or innovation-intensive economies. Recent evidence on governance-driven innovation also shows that board structure, gender diversity, and leadership quality can foster environmental innovation and strengthen firms' decarbonization strategies, especially in the energy sector (Mansour et al., 2025). This reinforces the idea that governance reforms are needed if eco-innovation is to become a primary lever in Tunisia's transition. Taken together, the evidence implies that H1 is strongly validated for the finance channel, while the eco-innovation channel is only partially supported and appears to operate in a delayed, state-dependent manner.

Income dynamics display the expected EKC signs (positive income, negative squared income) but remain statistically fragile across estimators and quantiles, implying that Tunisia is still on the rising segment where infrastructure needs and industrial expansion dominate composition and technique effects. Any turning-point calculation would therefore be premature, a conclusion consistent with studies showing delayed or absent turning points in fossil-intensive, institutionally constrained economies. This result nuances more optimistic EKC findings and suggests that income alone is unlikely to deliver decoupling without complementary changes in finance, technology, and the energy mix. Sustained decarbonization would require renewable deployment and eco-innovation to outpace GDP growth, as observed in some emerging economies undergoing structural transformation.

Energy composition exhibits a much clearer and more robust asymmetry, which directly bears on H2. Renewables lower carbon intensity, and their effects strengthen at higher quantiles (for example, at $\tau \approx 0.70$, $\beta \approx -0.08$), consistent with rising mitigation returns in high-intensity states (Gielen et al., 2019; Khan et al., 2024). Fossil energy is positive and strongly significant across specifications (with coefficients around +0.23), reflecting a carbon lock-in rooted in a gas-heavy power system and legacy subsidies (McCollum et al., 2014; Saleem et al., 2020). Compared with neighbors such as Morocco and Egypt, where renewable energy programs and energy-mix diversification are more advanced, Tunisia's decarbonization gains at comparable income levels remain more modest (IEA, 2024b, 2024c; IRENA, 2024b, 2024c). Morocco already obtains roughly 45–46% of its installed electricity capacity from renewables and targets at least a 52% renewable-capacity share by 2030, supported by large solar and wind programs in the Ouarzazate complex and Atlantic corridors (IEA, 2024b; IRENA, 2024b). Egypt likewise aims for about a 42% share of renewable electricity by 2030–2035, underpinned by flagship projects such as the Benban solar park and large wind complexes in the Gulf of Suez (IEA, 2024a; IRENA, 2024a; World Bank, 2024). The fact that Tunisia's power system remains around 95–97% fossil fuel-based despite comparable regional ambitions reinforces our interpretation of an energy-mix-constrained transition driven by slower project deployment, tighter fiscal space, and more

binding institutional constraints (World Bank, 2024; U.S. Department of Commerce, 2024). Dynamic tests corroborate this structure: fossil use and carbon intensity form a feedback loop, while the significant direction involving renewables runs from renewables to carbon intensity, with the reverse path at most marginal in short-run predictability (Granger, 1969; Toda & Yamamoto, 1995). Related work shows that domestic and international technology transfer can shape emission trajectories precisely through such energy-system channels (Wei & Zeng, 2025). Compared with studies that find stronger renewable-driven decoupling in more diversified systems (Doğanlar et al., 2021; Guan et al., 2023; Khan et al., 2024), Tunisia's pattern underlines the importance of accelerating grid integration, storage, and regulatory stability (Aktaş, 2020; Gajdzik et al., 2023; Oryani et al., 2021). In terms of H2, the income-emissions non-linearity is weakly identified, but the energy-mix component is clearly validated: a higher renewable share mitigates emissions, whereas greater fossil energy consumption intensifies them.

Openness and demography exert upward pressure mainly through scale and consumption channels, which is the core mechanism behind H3. Openness shows positive coefficients in several specifications but does not robustly Granger-cause emissions, a result consistent with composition and technique effects that materialize slowly and may elude short-run tests (Antweiler et al., 2001; Copeland & Taylor, 2004; Shahbaz et al., 2016; Adeleye et al., 2023). This contrasts with evidence for more diversified economies where openness, together with strong regulation, can reinforce cleaner production (Koengkan & Fuinhas, 2022; Öztürk, 2025). In Tunisia's case, trade and investment integration appear to reinforce emissions primarily through scale effects in medium-tech and energy-intensive sectors, with limited evidence so far of strong technique-driven emission reductions. Demographic pressure is positive in the cross-section of estimators and displays horizon-specific asymmetry dynamically: a long-run push from demography to carbon intensity alongside short-run feedback from high-intensity episodes to movements in the demographic-pressure index, plausibly through urbanization, energy-price, or labor-market channels (Ehrlich & Holdren, 1971; Martínez-Zarzoso & Maruotti, 2011; Arora et al., 2018). These patterns are consistent with STIRPAT-type formulations, where population, affluence, and technology interact in non-linear ways (Dietz & Rosa, 1994; Shahbaz & Sinha, 2019), and nuance more optimistic views that openness and demographic transition will automatically deliver environmental improvements in middle-income countries.

Viewed jointly, the results depict a transition that is finance-anchored and policy-driven but constrained by a fossil-heavy energy mix and slow innovation diffusion. In hypothesis terms, the evidence points to a robust financial channel and a clearly identified energy-mix channel, whereas eco-innovation and openness play weaker, state-dependent roles, and demographic dynamics emerge as a persistent driver of emissions (Popp, 2019; Losacker et al., 2023; Dunyo et al., 2024; Gielen et al., 2019; IRENA, 2024c; Shahbaz et al., 2013; Bekun et al., 2023). By aligning the empirical patterns with H1–H3 and situating them within both theoretical (financial intermediation, EKC, absorptive capacity, scale-composition-technique) and empirical contributions, the discussion confirms the expected dual contribution of the paper (Grossman & Krueger, 1995; Stiglitz & Weiss, 1981; Levine, 2005; Stern, 2017; Cohen & Levinthal, 1990). On the academic side, the study provides distribution-sensitive evidence on the joint roles of sustainable finance, eco-innovation, and the energy mix in a MENA economy, complementing work that has focused on advanced or large emerging economies and, in many cases, on mean effects only (Han & Jun, 2023; Sethi et al., 2024; Ozturk et al., 2024). From a policy perspective, these patterns motivate the differentiated responsibilities and instruments discussed below for bank-based, fossil-intensive economies such as Tunisia (Sachs et al., 2019; Taghizadeh-Hesary & Yoshino, 2020; Gielen et al., 2019; IRENA, 2024c). As a methodological caution, the

Granger and Toda–Yamamoto evidence documents temporal precedence and predictability rather than deep structural causation; the links should therefore be interpreted as lead-lag patterns consistent with the proposed mechanisms, and coefficients are read with the usual distinction between conventional ($p < 0.05$) and marginal ($0.05 \leq p < 0.10$) significance levels (Buchinsky, 1995; Koenker, 2005; Newey & West, 1987; White, 1980; Cochrane & Orcutt, 1949; Prais & Winsten, 1954).

On the policy side, the results translate into differentiated responsibilities for clearly identified stakeholder groups. At the macro-financial level, central banks, financial supervisors, and ministries of finance are key actors for designing credible sustainable finance frameworks, including taxonomies aligned with international practices, disclosure and verification rules that limit greenwashing, and prudential or risk-based incentives that encourage banks to expand climate-aligned lending (Sachs et al., 2019; Taghizadeh-Hesary & Yoshino, 2019; Sethi et al., 2024). Public development banks, guarantee funds, and commercial banks then operationalize these frameworks by originating and structuring green loans, guarantees, and bonds, and by building project-preparation capacity for small- and medium-sized renewable energy and energy-efficiency investments. To deepen this role, banks and development-finance institutions can develop labeled green-bond programs, climate-linked credit lines, and blended-finance vehicles that lower the cost of capital for renewable and efficiency projects, while public-private partnerships help aggregate and de-risk pipelines of small- and medium-sized investments, especially in energy efficiency, distributed solar, and green transport (Mejía-Escobar et al., 2020; Shi et al., 2023). At the regional level, Tunisia could leverage emerging African green-finance frameworks to standardize instruments, pool risk, and co-finance cross-border clean-energy and grid-integration projects, thereby amplifying the mitigation effects documented in this study (NDC Partnership, 2025; Sachs et al., 2019). Overall, the empirical findings highlight that strengthening the credibility and integrity of sustainable finance instruments is a prerequisite for scaling green investment in semi-industrialized, bank-based systems.

On the energy side, ministries in charge of energy and environment, independent regulators, and state-owned utilities constitute the core stakeholders responsible for translating financial signals into effective decarbonization. For semi-industrialized economies such as Tunisia, where the power mix remains dominated by fossil fuels, reforms of tariff structures, subsidy schemes, procurement rules, grid access, and long-term planning are required to reduce carbon lock-in and make renewable projects bankable at scale (McCollum et al., 2014; Gielen et al., 2019; IRENA, 2024c). Industrial firms, municipalities, and households are the downstream beneficiaries of these reforms, as credible green-finance instruments and energy sector reform can expand access to clean technologies, lower exposure to fossil fuel price shocks, and support a broader green-growth strategy. Overall, the results indicate that well-designed green policies—understood as coherent packages of sustainable finance regulation, innovation support, and energy sector reform—can play a central role in promoting sustainable development in semi-industrialized economies. In line with recent evidence on governance-driven environmental innovation (Mansour et al., 2025), strengthening board-level and regulatory governance around green-finance and innovation policies would further increase the effectiveness of these instruments in supporting Tunisia's low-carbon transition.

6. Conclusions, Policy Implications, and Future Research

This paper examined how sustainable finance, eco-innovation, income, openness, demography, and the energy mix shape Tunisia's low-carbon transition over 2000–2023, using mean and distribution-sensitive econometric approaches. The results show that sustainable finance is consistently associated with lower carbon intensity across specifications

and emission regimes, that renewable energy mitigates emissions while fossil energy use increases them, and that eco-innovation exerts mitigation effects mainly in high-intensity states. Income dynamics display the expected nonlinear pattern but are not strongly identified, while openness and demographic pressures tend to raise emissions through scale and consumption channels. Taken together, these findings suggest that Tunisia's transition is finance-anchored and energy-mix-constrained, with innovation and structural factors limiting the speed of decoupling.

The study contributes to the literature by providing distribution-sensitive evidence for a North African, bank-based economy and by integrating financial, technological, and structural drivers within a unified empirical framework. It highlights that average effects can mask important asymmetries across the emissions distribution and shows that sustainable finance and the energy mix are the primary levers of Tunisia's current decarbonization trajectory, while innovation and income dynamics play more gradual, state-dependent roles.

The policy implications are threefold. First, strengthening sustainable finance frameworks and project pipelines is essential. The results point to the need for credible taxonomies, robust labeling and verification rules, and monitoring systems that minimize greenwashing risks and ensure that green bonds, credit lines, and blended-finance vehicles generate additional and verifiable emission reductions. Instruments that effectively lower the cost of capital for low-carbon investments are particularly important in bank-based systems such as Tunisia's, where private investors are sensitive to regulatory certainty and risk-sharing mechanisms. Second, accelerating the restructuring of the energy system is crucial, particularly by scaling renewable capacity, improving grid integration and storage, and reducing structural dependence on fossil fuels. In semi-industrialized, gas-dependent systems, this requires coherent packages of power-sector reform—including tariff and subsidy reform, competitive renewable energy auctions, clear grid-connection rules, and long-term planning—so that sustainable finance flows can effectively translate into a cleaner energy mix and lower carbon intensity. Third, Tunisia needs to upgrade its innovation and governance ecosystem so that eco-innovation becomes a proactive rather than reactive force and to ensure that trade and investment openness facilitates cleaner technologies instead of reinforcing carbon-intensive activities. Careful design of price-signal reforms, accompanied by social protection measures, will be needed to manage the social and distributional impacts of the transition.

Overall, the findings indicate that green policies—understood as an integrated set of sustainable finance regulations, energy sector reforms, and innovation policies—can play a central role in promoting sustainable development in semi-industrialized economies. For Tunisia and comparable MENA and African countries, aligning these policy domains offers a pragmatic route to reconcile growth, energy security, and climate objectives.

The study has several limitations. It focuses on a single country and uses aggregate, macro-level indicators, which cannot capture firm- or sector-level heterogeneity. Some variables, including sustainable finance and eco-innovation, rely on proxies that may not fully reflect underlying quality or effectiveness. The empirical design identifies temporal patterns and predictive relationships rather than deep structural causality, and the results may be sensitive to unobserved shocks and measurement errors.

Future research could address these limitations by combining macro-level analysis with sectoral or firm-level data, by developing richer measures of green finance, governance, and innovation quality, and by extending the framework to multi-country panels in the MENA and African regions. Further work using structural or regime-switching models could also help clarify the mechanisms through which finance, innovation, and the energy mix jointly shape low-carbon transitions in bank-based, fossil-intensive economies.

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Abbreviations

The following abbreviations are used in this manuscript

GEFF	Green Economy Financing Facility
GCF	Green Climate Fund
STIRPAT	Stochastic Impacts by Regression on Population, Affluence and Technology
EKC	Environmental Kuznets Curve
HAC	Heteroskedasticity- and Autocorrelation-Consistent
OLS	Ordinary Least Squares
FGLS	Feasible Generalized Least Squares
BSQR	Bootstrapped Simultaneous Quantile Regression
ADF	Augmented Dickey-Fuller
PP	Phillips-Perron
ARDL	Autoregressive Distributed Lag
KOF	KOF Globalization Index
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
WDI	World Development Indicators
INS	Institut National de la Statistique (Tunisia)

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