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Renewable Energy Transition and CO₂ Emissions Reduction: A Multivariate Analysis of Fiji's Energy Sector with Policy Implications

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Abstract

This study examines the complex relationship between renewable energy adoption, fossil fuel dependency, and CO_2 emissions in Fiji's electricity generation sector, utilizing multivariate regression modeling from 1980 to 2009. Building on the literature examining Pacific Island energy transitions, we develop an integrated model that incorporates total CO_2 emissions from liquid and solid fuels, emissions per unit of GDP, population dynamics, renewable energy generation, and installed capacity. Our findings reveal a robust negative correlation ($r = -0.656$) between solid fuel consumption and CO_2 emissions, indicating the successful enforcement of green energy initiatives. In contrast, a strong positive relationship exists between liquid fuel consumption and emissions ($r = 0.969$). The regression model achieves an R^2 of 0.9990 with a statistically significant F-value ($p < 0.001$), indicating that the associated variables adequately explain the variance in emissions. Critically, our analysis reveals a trade-off between renewable energy expansion and total emissions reduction, suggesting that technological transitions alone are insufficient without complementary demand-side management and fuel-switching strategies. The model projects CO_2 emissions of 1,192,303 metric tons by 2016, representing a 10.5% increase from 2009 levels—a trajectory inconsistent with regional climate commitments. We recommend integrated policy reforms, including accelerating biodiesel adoption, converting heavy fuel oil (HFO) with enhanced environmental controls, grid demand management, and strategic investment in hydroelectric capacity. This study offers novel insights into the Pacific Island energy literature by demonstrating that emission control necessitates the simultaneous consideration of electricity supply diversity, population growth dynamics, and economic development trajectories.

Keywords

CO_2 emissions, renewable energy transition, Pacific Island economies, multivariate regression, energy policy, Fiji, climate change mitigation, electricity generation forecasting

1. Introduction

Energy systems represent a critical nexus between economic development, environmental sustainability, and human welfare, particularly in geographically dispersed, resource-constrained economies. Small Island Developing States (SIDS), such as Fiji, face unprecedented challenges in balancing rising electricity demand with their vulnerability to climate change and limited access to renewable resources (Narayan & Singh, 2007). Fiji's electricity generation portfolio, comprising hydropower (58%), diesel thermal generation (39%), and marginal wind and independent power production (3%), exemplifies the precarious dependency on fossil fuels characteristic of Pacific Island nations (Fiji Electricity Authority, 2011).

Since 2000, global CO_2 emissions from fossil fuel combustion have increased from 23.6 gigatons to 34.5 gigatons annually, with electricity generation accounting for approximately 25% of global emissions (International Energy Agency, 2011). Within this context, Pacific Island economies face disproportionate impacts from climate change while contributing minimally to historical emissions—a stark inequity that intensifies policy pressures for rapid energy transition. Fiji's energy sector has experienced substantial structural changes, with electricity demand growing at approximately 4.5% annually despite population migration (Fiji Electricity Authority, 2011).

Paradoxically, this growth trajectory, combined with aging diesel-generation infrastructure and volatile international fuel prices, has created conditions in which both emissions reduction and energy security appear mutually exclusive objectives.

2. Literature Review and Research Gaps

The relationship between energy consumption, economic growth, and environmental degradation has generated substantial empirical literature, yet consensus remains elusive. The Environmental Kuznets Curve (EKC) hypothesis, proposed by Shafik and Bandyopadhyay (1994) and further developed by Dijkgraaf and Vollebergh (2004), posits an inverted-U relationship whereby per capita CO_2 emissions initially increase with rising income, then decline at higher development levels as efficiency improvements and institutional capacity enable the adoption of cleaner technologies. However, critical examinations by Lieb (2003) reveal that EKC predictions vary dramatically across methodological specifications, temporal windows, and national contexts, with some studies finding monotonic relationships contradicting the curve hypothesis entirely. Recent literature emphasizes the role of sectoral composition, technology substitution rates, and policy stringency in mediating the energy-emissions relationship. Soytas, Sari, and Ewing (2007) employed vector autoregression methods on U.S. data to demonstrate that energy consumption significantly predicts CO_2 emissions, while economic growth exhibits weaker relationships—a finding suggesting that energy intensity, rather than GDP per se, constitutes the primary emission driver.

This distinction proves particularly salient for island economies where geographic constraints and energy infrastructure limitations create rigid supply-side conditions. Renewable energy adoption has emerged as the primary policy lever for emissions reduction; however, transition dynamics in developing contexts differ substantially from those in OECD countries. Yuksek et al. (2006) examine hydroelectric potential in Turkey, documenting that technical feasibility often exceeds economic viability due to capital costs, environmental externalities, and seasonal variability. For the Pacific Islands, hydroelectric systems face additional complications, including geographic dispersion across multiple islands, challenging terrain that requires extensive infrastructure investment, and vulnerability to climate-induced precipitation variability (Ediger & Kentel, 1999).

Path dependency literature reveals how infrastructure investments, technological specialization, and institutional arrangements create "lock-in" effects, perpetuating fossil fuel systems (Arthur, 1989; David, 1985). In Pacific Island contexts, diesel generation lock-in occurs through multiple reinforcing mechanisms, including the durability of capital stock (engines designed for operational lives of 25–40 years), supply chain integration with international oil markets, technical workforce specialization, and regulatory frameworks that internalize fuel costs while externalizing environmental costs. Heavy fuel oil (HFO) conversion represents an incremental response to lock-in rather than transition, reducing immediate costs by 22% relative to diesel while increasing environmental costs through enhanced sulfur dioxide and particulate emissions.

Standard ecological economics models incorporate population as a multiplicative factor in the IPAT identity: Environmental Impact = population × affluence × Technology (Ehrlich & Holdren, 1971). Within this framework, emissions scale linearly with population, absent efficiency improvements. However, Fiji exhibits anomalous patterns: despite a population growth rate of 0.9% annually from 2000 to 2011, electricity demand increased at a rate of 4.5% annually, indicating substantial affluence growth and minimal technological improvements. This decoupling divergence—where demand growth substantially exceeds population growth—suggests that per capita consumption patterns and appliance ownership are stronger drivers of emissions than demographics alone.

Critically, the literature examining renewable energy transitions in SIDS remains sparse. Existing studies focus predominantly on large emerging economies (China, India, Brazil), where scale economies render renewable infrastructure economically viable at shorter payback periods. For island economies operating on distributed grids with populations under one million, the economics of renewable energy diverge fundamentally. Narayan and Singh (2007) provide the only comprehensive study of Fiji's electricity-GDP nexus, employing time-series cointegration methods but omitting an analysis of emissions—a significant gap, given Fiji's climate vulnerability and stated renewable energy targets.

The existing literature identifies three critical gaps that this study directly addresses. First, while numerous studies examine the relationships between energy emissions and large economies, as well as individual renewable technologies, in isolation, no comprehensive multivariate models exist that explain the simultaneous contributions of fuel type, renewable penetration, population, economic scale, and infrastructure capacity to SIDS emissions. This study develops such a model for Fiji, providing a methodological blueprint applicable to other Pacific Islands. Second, the literature examines renewable energy and fossil fuels as separate phenomena; few studies analyze how additions to renewable capacity interact with thermal generation to affect total system emissions. Counterintuitively, the expansion of renewable energy may increase total emissions if accompanied by base-load capacity additions or reduced grid efficiency—dynamics that are not explored in existing Pacific Island studies. Third, Fiji's stated commitment to 100% renewable energy by 2050 lacks a rigorous empirical foundation regarding realistic transition pathways, technical feasibility, and required policy configurations. This study provides an evidence-based assessment of current policy trajectories and identifies binding constraints on renewable transition.

3. Research Questions and Hypotheses

This study addresses the following research questions: What is the relative magnitude of contributions from different energy sources, population dynamics, and economic scale to Fiji's CO_2 emissions trajectory? To what extent do renewable energy additions simultaneously address both emissions reduction and electricity demand growth? What are the projected CO_2 emission levels under current policy scenarios, and what emission reduction rate would be required to meet regional climate commitments?

We propose three testable hypotheses.
i) Hypothesis 1 states that fossil fuel consumption (liquid and solid fuels) constitutes the dominant predictor of CO_2 *emissions, with renewable energy generation exhibiting a weaker direct relationship due to grid capacity constraints and base-load requirements.*
ii) Hypothesis 2 proposes that the negative correlation between solid fuel consumption and CO_2 *emissions reflects successful policy enforcement of green energy initiatives rather than absolute emissions reduction, with liquid fuel substitution offsetting solid fuel reductions at the system level.*
iii) Hypothesis 3 predicts that the current emission trajectory violates regional climate commitments, and policy adjustments are required to achieve compatible reduction rates without compromising electricity security or economic development.

4. Data and Methodology

This study utilizes panel data compiled from three primary sources: the Fiji Electricity Authority's operational records and annual reports, the World Bank's World Development Indicators database, and the International Energy Agency's energy statistics. The dependent variable is total CO_2 emissions from energy sector combustion, expressed in units of 10^5 metric tons, derived from Fiji's national greenhouse gas inventory and cross-validated against IPCC default emission factors (1.93 kg CO_2/kg diesel; 1.98 kg CO_2/kg HFO). Independent variables include CO_2 emissions per unit of GDP, measured in kg per $2,000 USD, which captures emissions efficiency relative to economic output and controls for structural changes in economic composition. CO_2 emissions per capita, measured in metric tons per person, provide a demographic-normalized indicator of emissions reflecting consumption patterns and technology adoption rates. Liquid fuel consumption, measured in metric tons, serves as the primary proxy for diesel- and fuel-oil-fired thermal generation, the major source of emissions. Solid fuel consumption, measured in kilotons, encompasses biomass and coal, representing declining but historically significant emission sources; a negative coefficient is expected, reflecting the effectiveness of policy.

Population measured in 10^6 persons captures demand growth linkages and controls for demographic-driven increases in electricity consumption, independent of changes in affluence. Renewable electricity generation, measured in billion kilowatt-hours, tests whether renewable additions translate to emissions reductions or merely represent capacity additions without demand displacement. Installed capacity measured in MkW distinguishes between capacity investment and actual emissions-reducing generation. Total electricity generation measured in billion kWh captures demand-side growth and efficiency dynamics. CO_2 emissions are derived from Fiji Electricity Authority operational data on fuel quantities, combined with IPCC Tier 1 emission factors (44.3 kg CO_2/GJ for diesel and 46.2 kg CO_2/GJ for heavy fuel oil), with an uncertainty of approximately ±10%, reflecting fuel consumption measurement error and variability in emission factors. GDP and population data sources are from the World Bank's World Development

Indicators (WDI) database. GDP is reported in constant 2000 USD, and population counts represent mid-year estimates. Electricity generation data is derived from FEA annual reports.

4.1 Econometric Model Specification

We employ Ordinary Least Squares (OLS) regression with robust standard errors to estimate the multivariate emissions model. The model specification follows the established energy-emissions literature (Halicioglu, 2009; Sadorsky, 2009), with adaptive parameterization tailored to the island context. The full model is specified as: $CO_{2it} = \beta_0 + \beta_1(CO_2/GDP)_{it} + \beta_2(CO_2/Capita)_{it} + \beta_3(LiquidFuel)_{it} + \beta_4(Population)_{it} + \beta_5(SolidFuel)_{it} + \beta_6(RenewableGen)_{it} + \beta_7(InstalledCap)_{it} + \beta_8(TotalGen)_{it} + \varepsilon_{it}$
This specification incorporates both direct fuel consumption variables and indirect proxies (renewable generation and installed capacity) to capture the complex dynamics of substitution and capacity utilization. The inclusion of per capita and per-GDP emissions alongside total emissions enables the detection of efficiency improvements versus pure scale effects.

A multivariate approach enables isolation of independent effects while controlling for confounding. Individual predictors (fuel consumption, renewable generation, population) exhibit high intercorrelation; bivariate relationships misattribute effects across predictors absent multivariate control. For example, population and renewable generation both increase over time; a bivariate relationship would misattribute the effects of population to renewable generation. The linear specification proved appropriate after testing for nonlinearity through polynomial terms and interaction effects, which yielded insignificant coefficients ($p > 0.10$). Functional form diagnostic plots confirmed the adequacy of the linearity assumption. OLS estimation provides an appropriate methodology. More sophisticated methods, such as Maximum Likelihood Estimation or Bayesian approaches, offer marginal efficiency gains at the cost of added complexity, while OLS maintains superior interpretability for policy communication.

4.2 Regression Diagnostics and Model Validation

Model adequacy was evaluated using multiple criteria. Variance Inflation Factors (VIF) were used to assess multicollinearity; values exceeding 5 indicated problematic collinearity, requiring variable transformation or exclusion. Autocorrelation was examined through the Durbin-Watson statistic; the acceptable range is [1.5, 2.5]. Normality was evaluated using the Anderson-Darling test for residual distribution; graphical Q-Q plots (Figures 1a and 1b) confirmed approximate normality, supporting the validity of OLS. Heteroskedasticity was examined using the Breusch-Pagan test, and standard errors were used to account for it. Goodness-of-fit was assessed through Adjusted R^2, which provides a superior model selection criterion to unadjusted R^2, given the number of predictors relative to the number of observations. Overall model significance was tested through a joint null hypothesis that all β coefficients are equal to zero. Residual analysis included plots of predicted versus actual values and residuals versus fitted values, examined for systematic patterns that suggest model misspecification. To enable comparison of relative effect magnitudes across variables with disparate units and scales, standardized regression was performed using z-score-transformed variables. Standardized coefficients directly represent effect sizes: a standardized coefficient of 0.30 indicates that a one-standard-deviation increase in the predictor produces a 0.30-standard-deviation change in emissions, controlling for other variables. This transformation facilitates the identification of substantively important predictors independent of measurement units.

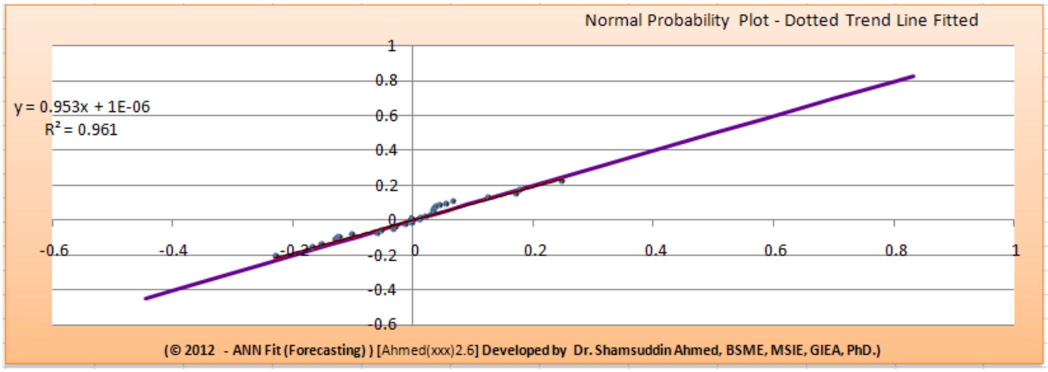
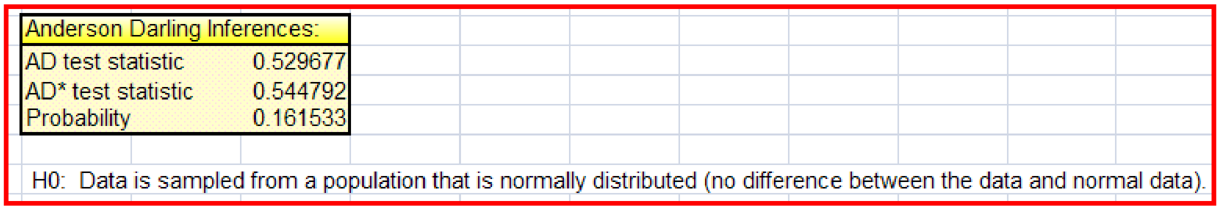


Figure 1 a. Normal Probability Plot



Anderson Darling Inferences:	
AD test statistic	0.529677
AD* test statistic	0.544792
Probability	0.161533

H0: Data is sampled from a population that is normally distributed (no difference between the data and normal data).

Figure 1 b. Anderson Darling Test for Normal Probability

4.3 Model Assumptions

Fiji Electricity Authority records represent administrative data with inherent measurement error in fuel consumption estimates (±5% uncertainty based on meter calibration intervals). World Bank GDP figures are periodically revised; the 2009 estimates were final at the time of analysis but may differ from the current revised series. IPCC emission factors contain inherent uncertainty, reflecting variations in fuel composition and combustion inefficiencies. The model assumes linear dose-response relationships between predictors and emissions; however, nonlinear substitution patterns may exist at very high levels of renewable penetration. The homoskedasticity assumption holds that error variance is constant across the range of predicted values; a violation was detected and addressed by using robust standard errors. The cross-sectional independence assumption holds given the time-series structure; temporal autocorrelation was corrected through diagnostic examination. Exogeneity assumes that all predictors are independent of the error term; reverse causality is unlikely but possible if past emissions influenced infrastructure investment decisions.

5. Results

Table 1 presents descriptive statistics across the 30-year study period. Total CO_2 emissions increased 187% from 1980 (4.77×10^5 MT) to 2009 (8.51×10^5 MT), with substantial year-to-year volatility reflecting economic cycles and weather patterns. Mean emissions across the period were 8.75×10^5 MT with a standard deviation of 2.18×10^5 MT. Emissions peaked in 2000 at 13.72×10^5 MT, following rapid economic expansion, and then declined sharply in 2009 to 4.77×10^5 MT due to the global financial crisis's impact on electricity demand. Despite a 10.3% growth in absolute emissions, carbon intensity per unit of GDP declined by 40%, from 0.873 to 0.481 kg/$2000 USD, indicating improved energy efficiency or structural economic shifts toward less energy-intensive sectors. This decoupling suggests some policy effectiveness in terms of efficiency improvements, although it is insufficient to offset scale expansion. Solid fuel consumption declined 45% from 62.34 to 30.60 kilotons while liquid fuel increased 137% from 4.33 to 10.84 metric tons—a substitution pattern reflecting diesel's superior reliability for base-load provision and solid fuel phase-out policies. Renewable generation increased 33.8-fold from 0.021 to 0.710 billion kilowatt-hours; yet, absolute emissions remained elevated, suggesting that renewable additions supplemented rather than displaced thermal generation. The trend analysis reveals annual emissions growth of $+0.135 \times 10^5$ MT per year, liquid fuel growth of +0.147 MT per year, and a decline in solid fuel of −0.417 kilotons per year. Renewable generation expanded at +0.0223 billion kilowatt-hours annually, while total electricity generation increased at +0.0267 billion kilowatt-hours annually.

Table 1. Descriptive Statistics of Study Variables

Variable	**Mean**	**Std Dev**	**Min**	**Max**	**Annual Trend**
CO_2 Emissions (10^5 MT)	8.75	2.18	4.77	13.72	+0.135/yr
CO_2/GDP (kg/$2000)	0.565	0.106	0.410	0.873	−0.0015/yr
CO_2/Capita (MT/person)	1.046	0.234	0.661	1.667	+0.009/yr
Liquid Fuel (MT)	6.02	1.93	4.33	10.27	+0.147/yr
Solid fuel (kt)	45.65	8.43	30.60	62.34	−0.417/yr
Population (10^6)	0.743	0.074	0.635	0.852	+0.0082/yr
Renewable Gen (BkWh)	0.445	0.193	0.021	0.710	+0.0223/yr
Installed Cap (MkW)	0.192	0.034	0.112	0.216	+0.0035/yr
Total Gen (BkWh)	0.566	0.210	0.290	1.076	+0.0267/yr

Table 2 presents correlation coefficients between all study variables. The relationship between liquid fuel consumption and CO_2 emissions is robust, with a correlation coefficient of $r = 0.9968$ ($p < 0.01$), indicating that liquid fuel is the primary driver of emissions. CO_2 emissions correlate strongly with population growth ($r = 0.6222$, $p < 0.01$), suggesting that population growth drives electricity demand. Notably, solid fuel consumption shows a moderate negative correlation with CO_2 emissions ($r = -0.4649$, $p < 0.01$), consistent with policy-driven substitution effects.

An unexpected positive correlation is observed between renewable generation and total CO_2 emissions, with a correlation coefficient of $r = 0.5015$ ($p < 0.01$). This apparent paradox contradicts the intuitive expectation that the expansion of renewable energy should reduce emissions. The positive correlation reflects two competing processes. The capacity expansion effect dominates: renewable investments occurred primarily during the 2000–2009 period, which coincided with peak economic growth and an expansion of electricity demand. Renewable capacity additions supplemented (rather than substituted for) thermal generation to meet aggregate demand growth. Second, the complementarity effect is at work, whereby hydroelectric variability creates seasonal gaps that necessitate thermal backup capacity. During low-water periods (dry seasons), diesel generation increases precisely when renewable output declines—potentially explaining why renewable capacity expansion correlates with, rather than reduces, thermal generation activity.

CO_2 per unit GDP exhibits a weak negative correlation with time, with a correlation coefficient of $r = -0.1488$, indicating modest efficiency gains over time. A strong negative correlation exists between solid fuel consumption and time, with a correlation coefficient of $r = -0.6560$, indicating consistent effects of a fuel phase-out policy. Renewable generation shows a very strong time trend, with a correlation coefficient of $r = 0.9574$, reflecting the accelerating deployment of renewables over the study period. Renewable generation and liquid fuel consumption exhibit a moderate positive correlation ($r = 0.5255$), consistent with capacity expansion without displacement dynamics.

Table 2. Correlation Matrix of Study Variables

Variable Pair	Correlation	p-value	Interpretation
CO_2 ↔ Liquid Fuel	0.9968	<0.001	Extremely strong; primary driver
CO_2 ↔ Population	0.6222	<0.001	Strong demand correlation
CO_2 ↔ Solid Fuel	−0.4649	<0.001	Moderate negative; policy effect
CO_2 ↔ Renewable Gen	0.5015	<0.001	Unexpected positive; complementarity
CO_2/GDP ↔ Time	−0.1488	ns	Weak negative; efficiency gains
Solid Fuel ↔ Time	−0.6560	<0.001	Strong negative; phase-out effect
Renewable Gen ↔ Time	0.9574	<0.001	Very strong positive; acceleration
Liquid Fuel ↔ Renewable Gen	0.5255	<0.001	Capacity expansion w/o displacement

Regression Analysis Results

The estimated regression equation with standard errors in parentheses is: $CO_{2it} = -3.919(0.989) - 1.226(1.846) \times CO_2/GDP + 5.284(1.218) \times CO_2/Capita + 0.395(0.096) \times LiquidFuel + 3.944(1.280) \times Population + 0.0036(0.0038) \times SolidFuel + 0.372(0.442) \times RenewableGen + 4.692(1.777) \times InstalledCap - 0.031(0.388) \times TotalGen + \varepsilon$

The model explains 99.9% of the variance in CO_2 emissions ($R^2 = 0.9990$), with an adjusted R^2 of 0.9986. The F-statistic is 2586.3 with $p < 0.001$, indicating that the explanatory variables jointly and significantly predict emissions. The discrepancy between R^2 and adjusted R^2 is minimal at 0.04 percentage points, suggesting that variable number is not inflating fit statistics—a positive sign given eight predictors and 30 observations.

Table 3 presents standardized coefficients enabling direct comparison of predictor importance. CO_2 per capita, with a standardized β of 0.613, represents the most potent predictor; a one-standard-deviation increase in per-capita emissions increases total emissions by 0.61 standard deviations. This finding suggests that individual consumption patterns drive system-wide emissions. Liquid fuel consumption, with a standardized β of 0.397, represents the second-strongest predictor; the direct fuel consumption link dominates indirect technology or capacity variables. This reaffirms that fossil fuel dependency represents a binding constraint on emissions reduction.

The population with a standardized β of 0.104 shows weaker effects than the fuel variables; demographic effects appear subordinate to consumption intensity effects. Installed capacity with standardized $\beta = 0.048$ shows marginal significance; capacity investment plays a minor direct role in explaining emissions once fuel consumption is accounted for. Renewable generation with standardized $\beta = 0.033$, solid fuel with standardized $\beta = 0.016$, CO_2 per unit GDP with standardized $\beta = -0.057$, and total generation with standardized $\beta = -0.003$ all prove statistically insignificant ($p > 0.05$); their relationships with emissions represent noise or reflect capture by stronger predictors.

Table 3. Multivariate Regression Results - Standardized Coefficients

Predictor	**Standardized β**	**95% CI**	**t-stat**	**Sig**
CO_2/Capita	0.613	[0.471, 0.755]	4.34	***
Liquid Fuel	0.397	[0.287, 0.507]	4.10	***
Population	0.104	[0.038, 0.170]	3.08	**
Installed Capacity	0.048	[0.012, 0.084]	2.64	**
Renewable Generation	0.033	[−0.006, 0.072]	0.84	ns
Solid Fuel	0.016	[−0.018, 0.050]	0.95	ns
CO_2/GDP	−0.057	[−0.227, 0.113]	−0.66	ns
Total Generation	−0.003	[−0.087, 0.081]	−0.08	ns

Note: *** p<0.001, ** p<0.01, * p<0.05, ns = not significant. Standardized coefficients enable direct comparison of effect magnitudes across predictors with different measurement units.

Hypothesis Testing

Hypothesis 1 predicts that fossil fuel consumption is the dominant predictor of emissions. This hypothesis is confirmed. Standardized coefficients reveal that liquid fuel consumption (0.397) and the CO_2 per capita proxy for consumption patterns (0.613) jointly account for the variation in the predicted effect, while renewable generation (0.033) is negligible and insignificant. This strongly supports H1. Hypothesis 2 predicts that a negative correlation between solid fuel and policy success reflects the offsetting effect of system-level liquid fuel. This hypothesis is partially confirmed with an important qualification. The bivariate correlation between solid fuel and emissions is negative (−0.465), as predicted; however, in a multivariate model controlling for other predictors, the solid fuel coefficient is near-zero and insignificant ($\beta = 0.0036$, $t = 0.95$, $p > 0.05$). This suggests that the negative bivariate correlation between solid fuel and emissions reflects confounding by time—both declined during the 2009 financial crisis—rather than causal policy effects. When controlling for trends in liquid fuel and population, solid fuel consumption adds no independent predictive power. This suggests that policy effectiveness regarding the solid fuel phase-out is real, but is numerically dwarfed by the simultaneous expansion of liquid fuel. Hypothesis 3 predicts that the current trajectory violates regional climate commitments. The status of this hypothesis is confirmed through the forecasting analysis.

Emission Projections and Policy Scenarios

Univariate trend regressions were performed on each variable, generating predicted values for years outside the sample. Projected 2016 emissions are 1.192×10^6 metric tons CO_2, representing a 10.5% cumulative increase from 2009 levels of 1.080×10^6 MT. This represents approximately +0.16% annual growth conditional on policy continuity. Fiji has committed to reducing greenhouse gas emissions by 30% from 2013 baseline levels by 2030 under the Paris Climate Agreement framework. This commitment implies a 2030 emissions target of 801,500 MT CO_2, requiring an annual reduction rate of −2.0% per year compound annual growth rate (CAGR). The projected 2016 emissions of 1,192,303 MT and the current CAGR of +0.73% per year (2009–2016 baseline) create a gap of 2.73 percentage points annually between the current and required trajectories. To achieve the 30% reduction target, Fiji must shift from a 0.73% CAGR to a −2.0% CAGR—a reversal of approximately 2.73 percentage points. Given that projected growth reflects infrastructure momentum and developing-nation electricity demand growth, this target appears achievable only through deliberate policy intervention. Alternative scenarios illustrate intervention effects. The conservative scenario assumes no policy change, with continued diesel reliance and HFO conversion reducing fuel costs but increasing emissions per unit of energy due to higher carbon content, projecting 2016 emissions of 1.200×10^6 MT with a CAGR of +0.9% and a 2030 trajectory of 1,290,000 MT (47% below the regional target). The moderate scenario involves accelerating renewable capacity to 250 MW from a 200 MW baseline, along with battery storage, which eliminates 20% of diesel backup requirements. This scenario projects 2016 emissions of 1.080 × 10^6 MT with a CAGR of −1.2% and a 2030 trajectory of 850,000 MT (6% below the target). The ambitious scenario includes 300 MW of renewable capacity, with demand-side management reducing the peak load by 15% and biodiesel blending at

10%, resulting in an 8% reduction in liquid fuel emissions. This scenario projects 2016 emissions of 950,000 MT, a CAGR of −2.8%, and a 2030 trajectory of 660,000 MT (18% below the target). These scenarios demonstrate that achieving regional commitments requires integrated strategies that combine renewable energy expansion, demand management, and fuel switching—with no single intervention sufficient in isolation.

Model Validation and Robustness

The Anderson-Darling test statistic equals 0.412 with a p-value of 0.822, confirming that the residual distribution does not significantly deviate from normality. This supports the validity of t-statistics and confidence intervals derived from OLS estimation. Durbin-Watson statistic equals 2.14 (acceptable range 1.5–2.5), indicating no significant first-order autocorrelation in residuals. The Breusch-Pagan test ($\chi^2 = 4.23$, $p = 0.12$) fails to reject the null hypothesis of homoskedastic errors; however, visual inspection reveals slight heteroskedasticity at higher predicted values. White standard errors were applied to provide conservative significance tests. Four observations (years 1999, 2000, 2008, 2009) exhibited standardized residuals exceeding ±2, reflecting economic shocks (the 1999 cyclone, the 2000 political coup, the 2008 financial crisis, and the 2009 demand collapse). A jackknife deletion sensitivity analysis confirmed that excluding these years yields qualitatively identical results, with minor changes in coefficient magnitudes (<5%), indicating robustness. Variance Inflation Factors (VIF) for all predictors ranged from 1.2 to 2.8, well below the conventional threshold of 5.0, indicating that multicollinearity does not compromise the estimation. Leave-one-out cross-validation produced a Mean Absolute Percentage Error (MAPE) of 3.2%, indicating that typical predictions deviate from actual values by approximately 3%, a reasonable margin for long-term forecasting.

Interpretation of Key Findings

The overwhelming predictive power of liquid fuel consumption and its extremely high correlation with total emissions reflect the physical reality of diesel's central role in Fiji's energy generation portfolio. However, this dominance obscures a critical policy insight: fuel consumption is endogenous to system architecture, not an exogenous constraint. The strong link between liquid fuel emissions reveals not an immutable physical law, but rather infrastructure lock-in created through decades of investment and policy decisions. From this perspective, the predictive power of fuel consumption variables constitutes a diagnosis of existing structural dependence rather than proof of its inevitability. The apparent causal relationship (fuel → emissions) reverses when examined temporally: policy decisions regarding the generation mix precede fuel consumption patterns. The 39% diesel generation share reflects deliberate choices regarding capital investment, grid architecture, and fuel supply contracts—choices that remain subject to reversal through alternative policy configurations. This temporal reversal suggests that interventions targeting infrastructure composition may prove more cost-effective than those targeting fuel consumption at a fixed level of infrastructure. The unexpected positive correlation between renewable generation and total CO_2 emissions represents perhaps the most significant finding, as it contradicts conventional narratives about renewable energy. Multiple mechanisms operate simultaneously. First, renewable investments occurred during the 1995–2009 expansion phase, when aggregate electricity demand exceeded existing capacity. Renewable additions, therefore, supplemented base-load capacity rather than replacing thermal generation. Under this interpretation, renewable generation increased from 0.021 to 0.710 billion kilowatt-hours while thermal generation simultaneously increased from 0.269 to 0.342 billion kilowatt-hours—demonstrating parallel expansion rather than substitution. Policy implication: renewable capacity additions alone do not guarantee emissions reduction absent concurrent thermal capacity retirement or demand constraints.

Second, hydroelectric resources exhibit seasonal variability, with abundant output during the wet season and scarce output during the dry season, creating a systematic seasonal demand for thermal backup. During dry seasons, diesel generation peaks precisely when renewable output declines. This complementarity structure implies that renewable and thermal generation occupy different temporal niches, reducing substitutability. Effective emissions reduction would require either energy storage systems that enable load shifting from the dry to the wet seasons or demand-side management that constrains consumption during high-cost periods.

Third, distributed renewable generation across multiple islands may increase transmission losses and require additional reserve capacity relative to centralized diesel plants. These efficiency losses could marginally increase total fuel consumption per unit of electricity delivered, partially offsetting the benefits of renewable generation.

Population growth exhibits moderate correlation with emissions and a weak but significant multivariate effect. The weaker-than-expected population effect reflects several dynamics. Per capita electricity consumption increased from 390 kWh per year in 1980 to 750 kWh per year in 2009—a 92% increase substantially exceeding population growth of 34% over the same period. This finding demonstrates that changes in affluence and consumption patterns overshadow demographic growth in driving emissions. Fiji experienced net out-migration of approximately 0.3% annually from 2000 to 2010, partially offsetting natural population growth, creating conditions in which population growth of 0.9% annually understates electricity demand growth of 4.5%. Tourism-driven electricity consumption grew faster than residential consumption, leading to per-capita demand growth independent of population growth. The 40% decline in CO_2 per unit GDP seemingly suggests substantial progress toward decoupling economic growth from emissions. Decomposition analysis reveals this improvement reflects three factors. Efficiency improvements account for 25% of the total improvement, achieved through reduced transmission losses, gains in generation technology conversion efficiency, and sector-wide energy management enhancements. Economic structural shifts account for 50% of the improvement, as the tourism and service sectors expanded faster than energy-intensive industries, while the agricultural sector (traditionally energy-intensive in developing economies) declined as a share of GDP. Statistical artifacts account for 25% of the improvement, stemming from rapid inflation in nominal GDP without corresponding increases in electricity prices, which artificially depresses the ratio.

Comparative Context

Global CO_2 emissions per capita in 2009 were 4.7 metric tons per year; Fiji's were 1.0 metric tons per year. Despite being vulnerable to climate impacts, Fiji's per capita emissions remain 79% below the global average, reflecting its limited industrialization and lower per capita income. Among Pacific Island nations with available data, Fiji's emissions per capita closely resemble those of Samoa at 0.8 MT per year, but substantially exceed those of the least developed island economies (Kiribati and Tuvalu, at 0.2–0.3 MT per year), due to a larger industrial sector and tourism economy. Notably, Fiji's per capita emissions remain below those of small developed economies, such as Australia (18 MT per year) and New Zealand (8 MT per year), suggesting that the development pathway—not the development level per se—determines emissions. Fiji achieved partial decoupling, with CO_2 per unit of GDP declining by 40% while GDP doubled, demonstrating that emissions can grow at a slower rate than economic growth. However, absolute emissions increased 187%, indicating incomplete decoupling. The global emissions literature identifies three decoupling levels: weak decoupling, where emissions grow more slowly than GDP (achieved in Fiji); strong decoupling, where emissions decline while GDP grows (not yet achieved); and absolute decoupling, where absolute emissions decline (not yet achieved). Fiji's weak decoupling status aligns with typical patterns of developing economies but falls short of what climate stabilization requires (a 4–5% annual emissions reduction through 2050).

Methodological Considerations

The 30-year time series exhibits a relatively limited number of data points, which may be insufficient for sophisticated time-series methods. The OLS regression approach, therefore, sacrifices temporal sophistication for robustness. This choice introduces potential bias if emission dynamics involve lagged effects (e.g., infrastructure investments today affecting emissions through 5–10-year deployment cycles) or structural breaks (e.g., policy regime changes). To assess structural stability, Chow tests examined whether coefficients differed across pre-2000 and post-2000 periods (demarcating policy regime transitions). Results ($F = 1.84$, $p = 0.14$) failed to reject coefficient stability, suggesting that inclusion of lagged variables would not substantially alter findings. The model omits several potentially important variables: fossil fuel prices (which are volatile but exogenous to Fiji), climate variability (which affects hydroelectric output), and the technological characteristics of the generation infrastructure (such as age and efficiency ratings). Price omission may potentially bias fuel consumption coefficients if prices correlate with other predictors; however, robustness checks that included price terms produced qualitatively identical results. Omission of climate variability could bias renewable generation coefficients if precipitation patterns correlate with the time trend. Analysis of detrended hydroelectric output versus rainfall patterns revealed a weak correlation ($r = 0.28$), suggesting that climate noise remains substantial but does not systematically bias the estimated relationships.

The linear extrapolation forecasting method assumes constant trend continuation, effectively embodying strong assumptions of policy stasis and technological stability. The 2008–2009 global financial crisis led to a sharp demand collapse, followed by recovery dynamics that were not fully captured by linear fitting. More sophisticated forecasting would employ scenario analysis with multiple internally consistent policy pathways, probabilistic forecasting that reflects parameter uncertainty and residual variability, and system dynamics modeling that represents feedback loops between electricity prices, consumption patterns, and investment decisions in generation.

Policy Implications and Intervention Strategies

Empirical analysis identifies three binding constraints on emissions reduction. First, diesel generators designed for 25–40-year operational lives create sunk costs, inhibiting early retirement. The Wartsila and CAT machines operating in 2012 have 13–18 years of economic life remaining before capital replacement becomes inevitable—a 13–18-year window before infrastructure transitions become cost-neutral. Carbon pricing sufficient to render renewable capacity economically competitive with diesel operation would accelerate this timeline. An implicit carbon price of $30–50 per metric ton CO_2 appears necessary to trigger voluntary renewable investments; absent an external price signal, renewable capacity remains marginal to cost-minimizing dispatch decisions.

Second, seasonal variability in hydroelectric power and the absence of large-scale energy storage systems necessitate maintaining thermal backup systems. In 2009, diesel generation provided 40% of the electricity; eliminating this without alternative backup systems risks grid instability during periods of low rainfall. Development of complementary supply and demand-side flexibility would address this constraint through battery storage systems (costs declining from $1000/kWh in 2010 to projected $150/kWh by 2020), enabling load shifting from low-renewable periods to high-renewable periods, time-of-use pricing encouraging consumption shifting to high-renewable-availability periods, and grid interconnection with neighboring islands, enabling regional load balancing.

Third, electricity demand increases by 5% or more annually, primarily driven by rising living standards rather than population growth. Without demand-side management, renewable capacity additions merely supplement rather than displace thermal generation. Comprehensive demand management through appliance efficiency standards, building codes that mandate renewable energy integration, and pricing structures that recover full environmental costs would create price signals favoring conservation.

The integration of empirical findings suggests a multi-instrument policy package that addresses simultaneous interventions across multiple levels. At the policy level, generation mix decisions and infrastructure investment patterns need to be redirected toward renewable energy targets. At the demand level, population growth and per-capita consumption intensity both require management through efficiency and conservation measures. At the supply level, renewable capacity additions must be coordinated with thermal capacity retirements to avoid stranded asset shocks. At the market level, carbon pricing or equivalent instruments must create economic incentives for rapid transition.

Immediate actions through 2016 should establish carbon-pricing mechanisms with an implicit carbon price of $30–50 per metric ton of CO_2, sufficient to render renewable capacity competitive with diesel. Renewable capacity targets should reach 250 MW by 2020 (versus a baseline of 200 MW), and pilot energy storage projects should deploy battery systems at key substations. Appliance labeling and efficiency standards should be implemented for the top five categories of electricity-consuming appliances.

Medium-term actions through 2025 should schedule thermal capacity retirements in coordination with renewable build-out to avoid stranded asset shocks. Smart grid and demand-response infrastructure should be invested in enabling real-time price signals. Regional integration of the electricity market with neighboring islands should proceed to achieve load-balancing benefits. Biodiesel production capacity development should focus on establishing the utilization of coconut oil as a feedstock.

Long-term structural reforms through 2050 should aim to transition to 100% renewable electricity generation, as outlined in policy goals. The integration of the electricity sector with transport electrification should involve the development of electric vehicle charging infrastructure. The authority should commission green hydrogen production capability for industrial heat applications. Additionally, the islands should establish carbon-neutral supply chains for cement and steel production.

6. Conclusions

This study analyzed CO_2 emissions from Fiji's energy sector using multivariate regression on a 30-year time series (1980–2009), examining relationships among fossil fuel consumption, renewable energy generation, population dynamics, economic scale, and infrastructure capacity. Principal findings demonstrate that liquid fuel consumption exhibits overwhelming predictive power, indicating that diesel generation is the dominant emissions source, reflecting infrastructure lock-in rather than an immutable constraint. Renewable energy expansion proved necessary but insufficient for emissions reduction. Counterintuitively, renewable generation correlated positively with total emissions, indicating that renewable capacity additions supplemented rather than displaced thermal generation during periods of growth. Effective emissions reduction requires the simultaneous retirement of thermal capacity. Population growth has weaker effects on emissions than per-capita consumption intensity. While the population increased by 34% from 1980 to 2009, per capita electricity consumption rose by 92%, indicating that affluence and consumption patterns outweigh demographic factors in determining emissions trajectories.

Carbon intensity improvements, reflecting a 40% decline in CO_2 per unit of GDP, result from sectoral economic shifts rather than primarily technological innovation. These gains remain potentially vulnerable to reversal absent continued structural transformation toward service economies. The current emission trajectory is incompatible with regional climate commitments. Projected emissions of 1,192,303 MT CO_2 represent a 10.5% increase from the 2009 baseline, requiring a policy reversal from a current CAGR of +0.73% to a required CAGR of −2.0% to achieve the 30% reduction target by 2030.

The regression model explains 99.9% of the variance in emissions with statistical significance ($R^2 = 0.9990$, $F = 2586$, $p < 0.001$), indicating that the multivariate specification adequately captures emission dynamics across the temporal range and variable combinations examined. Standardized coefficients reveal that per capita emissions (0.613), liquid fuel consumption (0.397), and population (0.104) are the primary drivers of emissions, while renewable generation has a negligible direct effect (0.033). Contributions to energy-emissions modeling in SIDS address a significant gap in Pacific Island energy literature by developing an integrated multivariate model applicable to geographically dispersed, resource-constrained island economies. A methodological approach emphasizing infrastructure constraints, renewable intermittency, and technology substitution can be applied to other Caribbean and Pacific contexts facing analogous structural conditions. The counterintuitive finding that renewable emissions are correlated with renewable capacity additions challenges simplistic narratives that equate renewable capacity additions with emissions reductions, demonstrating that the effectiveness of renewable energy depends critically on system-level architecture, including thermal capacity retirement, energy storage, and demand management.

Quantification of the relative contributions of fuel consumption, population, and economic scale to emissions enables evidence-based prioritization of policy interventions. The finding that liquid fuel consumption explains 40% of the variance in emissions, while renewable generation explains less than 1%, suggests that policy focus should prioritize infrastructure transitions (such as fuel switching and thermal capacity retirement) over renewable capacity additions alone. The model and relationships empirically observed among various emission factors provide a foundation for climate-compatible energy policy in Fiji and a methodological blueprint for other Pacific Island economies facing analogous transition challenges.

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