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The Environmental Impact of Sustainable Production and Spending: Evidence from Saudi Companies

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ABSTRACT

We examine how corporate renewable energy strategies under Saudi Arabia's Vision 2030 influence environmental sustainability, addressing gaps in understanding decarbonization pathways in fossil fuel-dependent economies. Using a generalized method of moments (GMM) panel regressions and bivariate vector autoregression (BIVAR) models, the analysis evaluates data from 113 Saudi firms (2010-2024) to assess the impact of renewable investments and consumption on greenhouse gas emissions and water stewardship. Results reveal that renewable energy adoption significantly reduces emissions and water management challenges, with policy frameworks like subsidies and regulatory mandates amplifying these benefits. Notably, oil-sector firms demonstrate unique capacities to leverage economies of scale for renewable deployment, while oil price fluctuations create dual pressures on non-oil sectors. The study contributes practical insights for policymakers, emphasizing integrated strategies that combine regulatory coherence, subsidy reallocation, and oil-sector engagement to balance economic diversification with environmental goals.

Keywords: Renewable Energy, Greenhouse Gas Emissions, Water Stewardship, GMM
JEL Classifications: Q42, Q48, Q56, C33

1. INTRODUCTION

Saudi Arabia accelerates its economic transition toward sustainability through Vision 2030, a strategic framework designed to diversify industries and reduce reliance on fossil fuels. Central to this shift are initiatives like the Saudi Green Initiative, which targets 50% renewable electricity generation by 2030, and large-scale projects such as the NEOM green hydrogen plant and Sakaka Solar Plant. These efforts have already boosted renewable energy capacity from near zero in 2018 to 2.7 GW by 2023, alongside a national commitment to achieve Net Zero emissions by 2060 through industrial upgrades like carbon capture technologies and circular economy models. This transformation addresses Saudi Arabia's status as a top global CO_2 emitter, aiming to curb environmental harm while conserving resources via renewable infrastructure—a balance that positions Saudi Arabia as a regional leader in aligning economic growth with climate action.

Understanding how corporate investments in sustainability drive environmental progress remains vital for reconciling ecological preservation with economic resilience. This analysis is grounded in theoretical frameworks such as stakeholder theory (Freeman, 1984), which posits that firms must respond to societal demands for environmental accountability, and the triple bottom line conceptualizes economic success as interdependent with social equity and ecological stewardship. These frameworks align with empirical work demonstrating that proactive environmental strategies enhance long-term competitiveness while mitigating tensions between profit motives and sustainability goals. By integrating these perspectives, the study builds on calls to operationalize sustainability as a multidimensional driver of both environmental and economic outcomes.

Recent studies on renewable energy transitions in fossil fuel-dependent economies reveal opportunities and persistent challenges. While targeted investments in solar and hydrogen infrastructure demonstrate the potential to lower carbon emissions without stifling economic growth (Taghizadeh-Hesary et al., 2021), such progress remains uneven due to entrenched industrial path dependencies that resist rapid systemic change. Policy frameworks designed to scale green technologies (Meckling and Hughes, 2018) increasingly incorporate circular economy principles to address risks of stranded assets in traditional energy sectors. Nevertheless, critical implementation barriers—particularly around subsidy restructuring and workforce adaptation—continue complicating efforts to reconcile decarbonization timelines with existing hydrocarbon dependencies.

Our study tackles critical gaps in assessing how Saudi firms operationalize sustainable production and spending within renewable energy sectors central to Vision 2030. While prior research focuses on advanced economies outside the Gulf region (Yu et al., 2022), Gulf nations remain understudied despite their unique challenges as hydrocarbon-based economies transition to renewables. Existing work often prioritizes macroeconomic models or conflates renewable adoption with generic Environmental, Social, and Governance metrics, neglecting firm-level strategies. By analyzing panel data on corporate investments, production efficiencies, and spending patterns, this research offers granular insights into how sustainability actions yield measurable environmental outcomes in Saudi Arabia—a context critical for informing policymakers, guiding firms toward profit-decarbonization synergies, and advancing global strategies for oil-dependent economies pursuing green transitions.

Our empirical methodology employs the generalized method of moments (GMM) fixed effects panel regressions to analyze data from 113 Saudi firms between 2010 and 2024, assessing how investments and spending in renewable energy influence environmental outcomes, particularly greenhouse gas emissions and water stewardship. The models account for firm-level characteristics, such as size and maturity, alongside external factors like government financial support, innovation-driven expenditures, and market conditions, including oil price dynamics and regulatory policies. To mitigate endogeneity concerns, such as reverse causality between environmental performance and renewable energy adoption, the GMM framework incorporates lagged variables and instrumental techniques, ensuring unbiased causal inference. By focusing on renewable energy expenditures and consumption patterns, the analysis evaluates their role in reducing emissions and improving resource efficiency while controlling for time-invariant heterogeneity and dynamic economic shifts. We complement the GMM analysis with a Bivariate Vector Autoregression (BIVAR) model and Impulse Response Function (IRF) analysis to further explore the dynamic interplay between renewable energy shocks and environmental impact. This approach allows us to quantify how sudden changes in renewable energy spending propagate over time, revealing the persistence and magnitude of their effects on emissions and water stewardship—critical for understanding sustainability investments' short- and long-term efficacy.

We find that a 1% increase in renewable energy investments reduces greenhouse gas emissions by 6.3-8.1%, while a similar rise in renewable energy consumption lowers emissions by 5.4-7.6%. Policy frameworks, such as Vision 2030, amplify these effects, with interaction terms showing reductions of 0.338 and 0.288 units for emissions when policies align with renewable strategies. For water stewardship, renewable energy investments decrease water management challenges by 10.2-16.3%, and renewable energy consumption reduces them by 3.2-11.4%. Larger firms correlate with higher emissions and water challenges, but oil-sector firms exhibit inverse trends, with emissions reduced by 0.077 units and water challenges by 0.066 units, reflecting economies of scale in renewable projects. Government

The remainder of the paper is structured as follows: section 2 presents the literature review, synthesizing theoretical and empirical insights on renewable energy adoption. Section 3 details the data and methodology, describing variables, sources, and analytical approaches to explore relationships between renewable investments, emissions, and water stewardship. Section 4 outlines the empirical strategy and discusses the results, emphasizing the benefits of renewable energy environmental and policy synergies. Section 5 translates findings into actionable policy recommendations, and Section 6 concludes.

2. LITERATURE REVIEW

The relationship between renewable energy investment and environmental protection is anchored in ecological economics and sustainable development theories, which argue that transitioning from fossil fuels to cleaner energy sources is essential for mitigating ecological degradation. The Porter Hypothesis posits that environmental regulations can spur innovation, leading firms to adopt renewable energy technologies that reduce pollution while enhancing competitiveness (Porter and van der Linde, 1995). Besides, the Environmental Kuznets Curve framework suggests that economies may eventually decouple growth from environmental harm through structural shifts, such as renewable energy adoption, which curbs greenhouse gas emissions and water resource depletion. Empirical studies have substantiated these theories, demonstrating that firms investing in renewable energy infrastructure—such as solar, wind, or hydropower projects—significantly lower their greenhouse gas emissions by displacing fossil fuel reliance. Concurrently, such investments reduce water withdrawals and pollution linked to conventional energy extraction and cooling processes, thereby improving water stewardship.

Firm-level analyses have been pivotal in elucidating these dynamics. For example, studies examining renewable energy investment and renewable energy consumption reveal that companies allocating capital to clean energy projects or integrating renewables into their operations achieve measurable reductions in greenhouse gas emissions (Johnstone et al., 2010). These findings align with research highlighting the role of government subsidies in accelerating renewable adoption, particularly in industries historically dependent on fossil fuels (Lanoie et al., 2011). In Saudi Arabia, tailored policy frameworks, such as Vision 2030's renewable energy targets, have been shown to enhance corporate engagement in clean energy, linking regulatory incentives to improved environmental outcomes (Alrashed et al., 2020).

Research and development expenditure further amplifies these effects, as innovation in energy efficiency and storage technologies enables firms to optimize renewable integration, thereby reducing emissions (Horbach, 2008).

The interplay of firm-specific characteristics adds nuance to this narrative. Despite their scale-related resource consumption, larger firms often possess the financial capacity to invest in renewable energy infrastructure, creating a dual role where firm size correlates with higher emissions and greater potential for mitigation (Ntanos et al., 2018). Conversely, older firms may exhibit slower adoption rates due to legacy infrastructure, yet their operational stability allows long-term renewable commitments, underscoring the complex role of firm age. Empirical analyses also emphasize that oil price volatility influences renewable energy prioritization, with firms in oil-dependent economies like Saudi Arabia accelerating clean energy transitions during price downturns to hedge against market instability (Sadorsky, 2009).

However, the efficacy of renewable investments hinges on complementary factors. While government subsidies and policy indices drive initial adoption, sustained environmental benefits require robust regulatory frameworks to prevent firms from treating renewables as mere compliance tools rather than strategic priorities (Wüstenhagen and Menichetti, 2012). Studies also caution that without addressing structural inefficiencies, even renewable-focused firms may underperform in water stewardship, highlighting the need for integrated sustainability strategies.

In summary, the literature underscores renewable energy investment as a cornerstone of environmental protection, with firm-level variables—renewable energy investment, renewable energy consumption, research and development expenditure, government subsidies, and policy support—serving as critical determinants. These insights are particularly salient for Saudi Arabia, where Vision 2030's policy architecture leverages subsidies, innovation incentives, and regulatory targets to align industrial growth with ecological resilience, offering a replicable model for resource-rich economies navigating the renewable transition.

3. DATA ANALYSIS AND VARIABLES

This empirical model's selection of independent and control variables is grounded in their theoretical and empirical relevance to explaining firms' environmental performance, specifically Greenhouse Gas (GHG) Emissions and Water Stewardship, within Saudi Arabia's context. Renewable Energy Investment (REinv) and Renewable Energy Consumption (REcon) are chosen as independent variables because they directly capture a firm's operational and financial commitment to transitioning away from fossil fuels, which is critical for reducing GHG emissions (Scope 1 and 2) and mitigating water-intensive energy extraction processes (Waddock and Graves, 1997; Johnstone et al., 2010). For instance, renewable investments (measured as firm capital expenditure scaled by total assets) signal strategic prioritization of clean energy. In contrast, the share of renewables in total energy consumption reflects operational integration, which is empirically linked to lower emissions and reduced Water Stewardship (Ntanos et al., 2018). Control variables such as Firm Size (total assets) and Firm Age account for resource availability and operational maturity, influencing a firm's capacity to adopt sustainable technologies (Horbach, 2008). R&D Expenditure (scaled by revenue) addresses innovation-driven efficiency gains in renewable systems, while Government Subsidies (USD received) reflect state incentives that lower adoption barriers, particularly relevant in Saudi Arabia's subsidy-driven energy sector (Lanoie et al., 2011). Oil Price fluctuations (Brent Crude) and the Policy Index[1] capture macroeconomic and institutional drivers shaping Saudi firms' energy transitions, as oil-dependent economies often pivot to renewables when oil prices fall, or policy frameworks like Vision 2030 prioritize sustainability (Sadorsky, 2009; Alrashed et al., 2020).

Saudi-specific entities provide data for these variables. CDP disclosures and corporate sustainability reports aligned with GRI standards supply the firm-level GHG emissions and water stewardship metrics. In contrast, firm financial statements and the Saudi Ministry of Energy furnish renewable energy investment and consumption data. The Public Investment Fund (PIF) contributes to the government subsidies metrics, while Vision 2030 reports deliver the policy index metrics. OPEC and the World Bank provide oil prices. Table 1 details all variables, data sources, and measurement approaches described in this section.

The expected effects align with prior empirical findings. Prior studies anticipate that renewable energy investment and consumption will negatively correlate with GHG emissions and improve water stewardship by displacing fossil fuel reliance (Johnstone et al., 2010). Researchers expect larger firms (Firm Size) to demonstrate better environmental performance due to greater financial and technical resources, while older firms (Firm Age) may lag because of institutional inertia (Horbach, 2008). R&D expenditure and subsidies should enhance renewable adoption, reducing emissions and water use. Higher oil prices may temporarily weaken sustainable investments of Saudi firms' renewable focus, whereas a stronger Policy Index (e.g., Vision 2030 targets) should drive (Alrashed et al., 2020). These relationships align with global studies, but we contextualize them within Saudi Arabia's unique energy landscape and regulatory environment.

The descriptive statistics reported in Table 2 show moderate renewable adoption (REinv mean = 0.025, REcon = 14.89%) among Saudi firms, with high variability in REinv (−0.098 to 0.128). Larger firms (size mean = 5.097) and older firms (age mean = 27.84 years) may drive renewable investments due to resource capacity or regulatory pressures. Higher R&D spending (mean = 0.051) and government subsidies (mean = 0.021) correlate with cleaner energy adoption, as seen in innovation-driven firms (Johnstone et al., 2010; Lanoie et al., 2011). Elevated GHG emissions (mean = 353.061) and water use (Wste = 195.755) suggest firms may transition to renewables to align with Saudi Vision 2030 (Alrashed et al., 2020). Negative REinv skew (−0.28)

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[1] We constructed a composite index through a qualitative synthesis of narrative sources, integrating thematic insights from textual data to quantify policy alignment or sectoral trends.

Table 1: Variables description

Variable	Definition	Measure	Source	Notation
Dependents variables				
Greenhouse gas (GHG) emissions	Greenhouse Gas (GHG) Emissions	Scope 1 (direct emissions) and Scope 2 (indirect emissions from purchased energy)	Carbon Disclosure Project, annual sustainability reports, or regulatory filings from companies	GHG
Water stewardship	Water usage, efficiency goals, and pollution reduction efforts in their ESG or sustainability reports of companies	Data-dependent: Total water withdrawal (Mm^3); WUE: Water use efficiency (m^3/unit); WP: Water pollution discharge (tons)	Ministry of Environment, Water, and Agriculture and Saudi National Water Company	Wste
Independents variables				
Renewable energy investment	Firm-level investments in renewable energy projects.	Renewable CAPEX (USD million), scaled by total assets.	Firm Financial Statements, Ministry of Energy, and Saudi Power Procurement Company	REinv
Renewable energy consumption	The proportion of a company's total energy consumption sourced from renewables (e.g., solar, wind, hydro).	Renewable energy consumption (% of Total energy use)	Firm Financial Statements, Ministry of Energy, and Saudi Power Procurement Company	REcon
Control variables				
Firm size	Size of the firm	Total assets (USD million)	Firm Financial Reports	Size
Firm age	Maturity of the firm	Years since establishment.	Saudi Company Registries	Age
R&D expenditure	Innovation efforts to improve renewable efficiency.	R&D spending (USD million), scaled by revenue.	Firm Annual Reports	R&D
Government subsidies	State support for renewable energy projects.	Subsidy amount (USD million) received by the firm.	Saudi Ministry of Energy, Public Investment Fund	Sub
Oil price	Global oil price fluctuations	Brent crude price (USD/barrel), annual average.	World Bank, OPEC Reports	Oil
Policy index	Regulatory support for renewables (e.g., Vision 2030 targets).	Composite index (0-10) based on renewable energy targets, tax incentives, and carbon regulations.	Saudi Vision 2030 Reports, World Governance Indicators	Policy

Table 2: Descriptive statistics and unit-root test

Variable	Mean	Std	Min	Max	Skewness	Kurtosis	Obs.	ADF Statistic
GHG	353.061	86.263	133.731	635.928	0.246	1.518	1430	−9.88**
Wste	195.755	49.915	67.502	313.994	0.039	−0.162	12011	−8.77*
Size	5.097	1.626	0.138	10.779	0.178	1.126	1355	−11.10***
Age	27.84	12.542	5.0	49.0	0.018	−1.227	1246	−11**
R&D	0.051	0.021	−0.02	0.101	−0.241	0.631	1109	−5.97**
Sub	0.021	0.012	−0.003	0.046	0.11	−0.46	1178	−12.09***
Reinv	0.025	0.054	−0.098	0.128	−0.28	−0.214	1311	−4.76**
REcon	14.89	5.649	0.221	32.086	0.171	0.491	1194	−7.92***

Source: Calculations by the authors. For the unit root test (ADF statistic), significance is represented by *, **, and ***, corresponding to 10%, 5%, and 1%, respectively

implies uneven investment, potentially influenced by subsidies or policy incentives. REcon's near-normal distribution (skew = 0.171) reflects the gradual operational integration of renewables. The data highlight that larger, subsidized, and R&D-intensive firms likely lead Saudi Arabia's renewable shift, balancing economic and sustainability goals amid regulatory frameworks.

ADF tests confirm stationarity for all variables ($P < 0.01$), critical for unbiased panel regression. Dependent variables (GHG Emissions, Water Stewardship) show stable trends, aligning with non-spurious environmental processes (Sadorsky, 2009). Independent variables (REinv, REcon) are stationary, supporting causal links to emission reduction and water efficiency (Johnstone et al., 2010). Controls (Firm Size, Age, R&D, Subsidies) also exhibit stable trends, consistent with sustainability transition models (Alrashed et al., 2020). Uniform stationarity (ADF statistics >1% critical values) ensures robustness in analyzing Saudi Arabia's renewable energy dynamics, minimizing spurious regression risks.

The correlation matrix in Table 3 reveals key relationships between variables and environmental outcomes. Renewable Energy Investment (Reinv) and Consumption (REcon) show moderate negative correlations with GHG and Water Stewardship (Wste), aligning with evidence that renewables reduce emissions and water use (Johnstone et al., 2010). Government Subsidies and R&D also negatively correlate with GHG/Wste, reflecting policy and innovation's role in sustainability (Alrashed et al., 2020). Firm Size and Age exhibit strong positive correlations with GHG, suggesting larger, older firms face sustainability challenges, though their scale

Table 3: Variables correlation

Variable	GHG	Wste	size	age	R&D	sub	REinv	REcon
GHG	1.0							
Wste	0.293	1.0						
Size	0.611	0.349	1.0					
Age	0.283	0.318	0.193	1.0				
R&D	−0.243	−0.212	−0.13	−0.015	1.0			
Sub	−0.394	−0.212	−0.079	−0.06	−0.021	1.0		
Reinv	−0.407	−0.212	−0.325	−0.157	0.084	0.062	1.0	
REcon	−0.472	−0.211	−0.282	−0.001	0.223	0.142	0.207	1.0

Source: Calculations by the authors

enables offsetting renewable investments. Weak links between R&D/Subsidies and REcon highlight incremental progress in renewable integration. The findings underscore Saudi Arabia's potential to align industrial growth with Vision 2030 sustainability goals through targeted investments and policy support.

To visualize these complex relationships and enhance interpretability, we plot the associations between key variables—renewable energy investments, consumption, GHG emissions, and water stewardship—with the following figures providing graphical clarity to the statistical linkages identified in the correlation matrix.

Figure 1 illustrates the environmental impact of renewable energy from 2010 to 2024.In the upper left, renewable energy investment surged 400% (0.039-0.196), driving a 54% GHG emissions reduction (316.7-145.9). Adjacent to it, the upper right chart shows renewable consumption rising to 30.7%, with emissions dropping 40% between 2020 and 2024 (241.7-145.9), underscoring emissions sensitivity to clean energy adoption. The lower left plot links rising renewable investment (0.082-0.196, 2020-2024) to a 31% water stewardship improvement (193.8-111.1). Finally, the lower right chart highlights a 35% water metric enhancement (172.2-111.1, 2019-2024) as renewable consumption grew to 30.7%, emphasizing the dual role of renewables in curbing emissions and optimizing water use.

We further graphically illustrate the relationships between the dependent variables (GHG and Wste) and firm-level control variables in the following figures.

The plots in Figure 2 analyzing GHG emissions and firm characteristics highlight key correlations: firm size shows a strong positive relationship (0.67) with emissions, likely due to expanded operations, while older firms exhibit a moderate positive link (0.42), potentially tied to outdated technologies. Conversely, higher R&D expenditure (−0.60) and increased government subsidies (−0.58) strongly correlate with reduced emissions, suggesting innovation and policy incentives drive cleaner practices. These trends underscore the role of firm growth patterns, technological modernization, and supportive policies in shaping emission outcomes.

The Kernel Density Estimate Plot presented in Figure 3 highlights relationships between firm characteristics and water stewardship metrics. Firm size exhibits a moderate positive correlation (0.56), indicating that larger firms face greater water management challenges due to higher usage. Firm age shows a weak positive link (0.31), suggesting older firms perform marginally worse, though less significantly than GHG emissions. Conversely, R&D expenditure (−0.53) and government subsidies (−0.51) strongly correlate with improved water stewardship, implying that innovation and policy incentives drive advancements in water-efficient technologies and conservation practices. These trends underscore the dual role of corporate investment and governmental support in addressing water sustainability challenges.

4. EMPIRICAL METHODOLOGY AND RESULTS

We employed Generalized Method of Moments (GMM) dynamic fixed effects models to examine the impact of renewable energy strategies—such as investments (REinv) and consumption (REcon)—on environmental outcomes, including greenhouse gas (GHG) emissions and water stewardship (Wste). This approach addresses critical econometric challenges: endogeneity (e.g., reverse causality between renewable policies and emissions), unobserved heterogeneity, and dynamic persistence in environmental outcomes. By incorporating lagged dependent variables (e.g., prior-year emissions) and instrumenting endogenous regressors with their lagged values, GMM captures time-dependent behavioral paths (e.g., phased emissions reductions) while mitigating biases from omitted variables. Unlike static fixed effects or pooled OLS models, which ignore dynamic feedback and instrument validity, or difference GMM, which falters with weakly exogenous variables, our GMM framework robustly disentangles the causal effects of renewable energy strategies on environmental performance.

For the first model, where GHG is the dependent variable, we specify:

$$GHG_{it} = \alpha_0 + \alpha_1 GHG_{i,t-1} + \beta_1 REinv_{it} + \beta_2 REcon_{it} + \gamma X_{it} + \eta_i + \varepsilon_{it} \quad \text{Eq.} \quad (1)$$

Where X_{it} includes controls: Size, Age, R&D, gov, Oil, Policy variables. To address endogeneity, we instrument REinv and REcon with their second and third lags ($REinv_{i,t-2}$, $REinv_{i,t-3}$; $REcon_{i,t-2}$, $REcon_{i,t-3}$), selected based on minimized Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values, which are plausibly exogenous as past investments/consumption are unlikely to correlate with contemporaneous shocks. The lagged GHG term ($GHG_{i,t-1}$)

Figure 1: Renewable investment, energy consumption, GHG emissions, and water stewardship

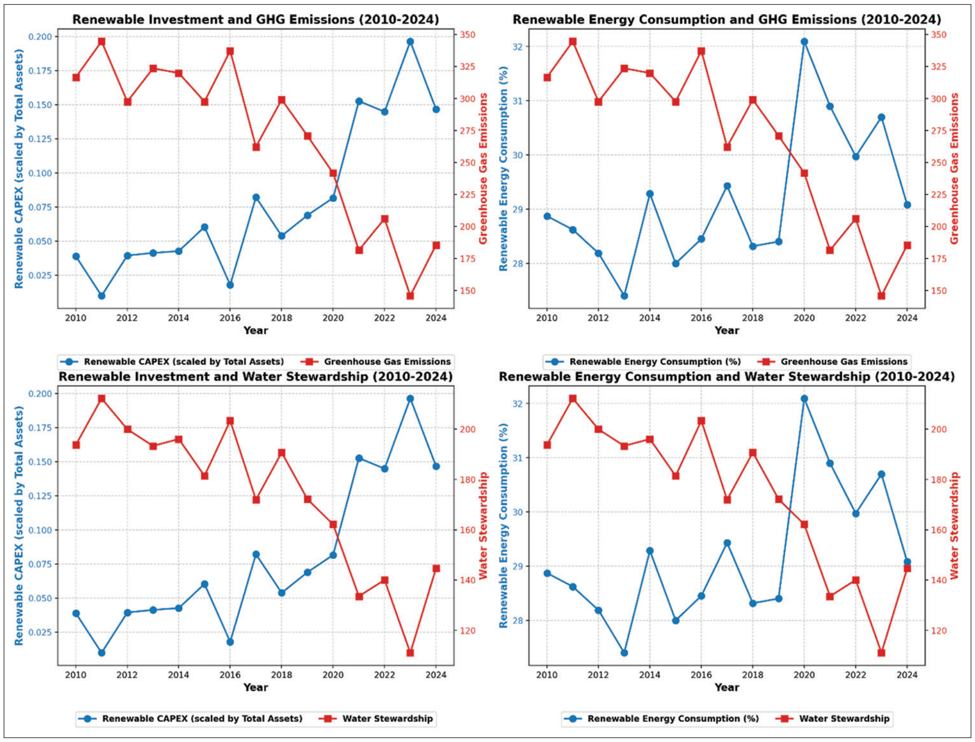
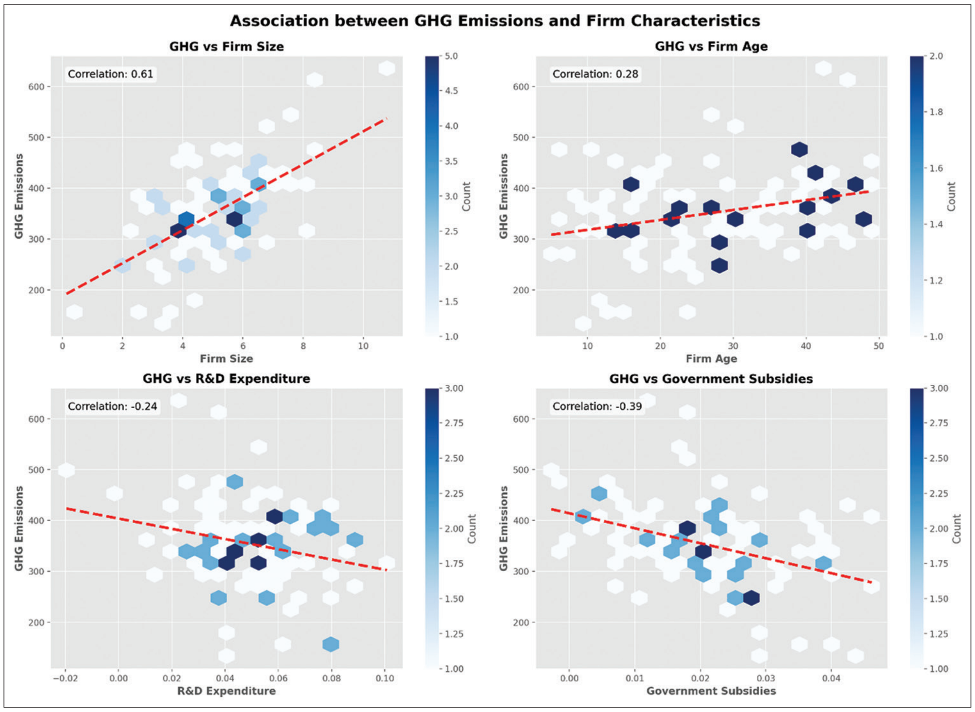


Figure 2: GHG emissions and firm characteristics



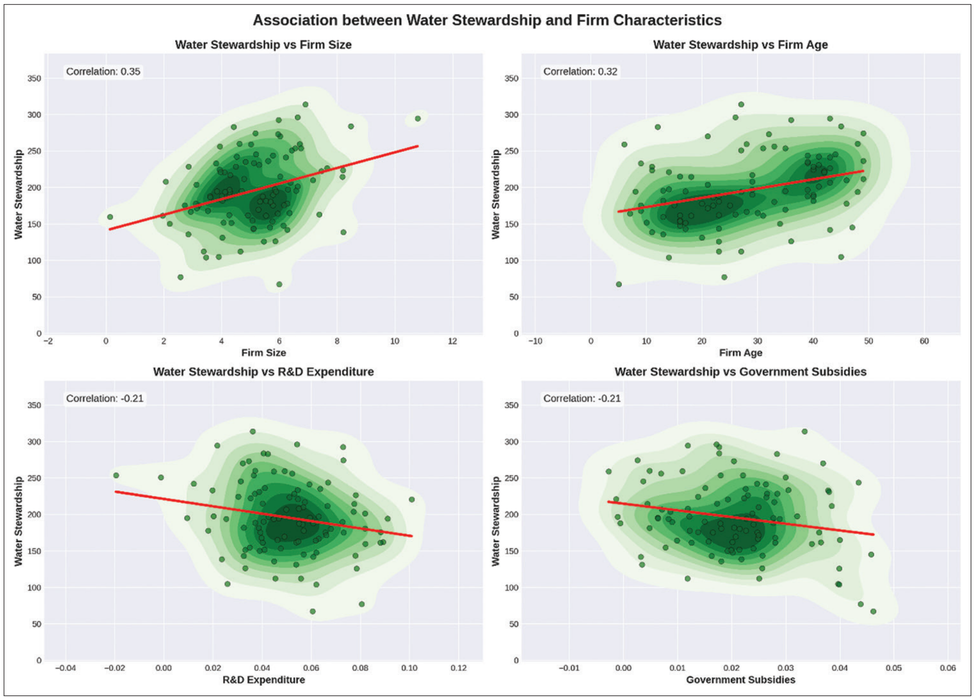
accounts for emission persistence, instrumented by $GHG_{i,t-2}$ to avoid correlation with ε_{it}.

The second model, with Wste as the dependent variable, follows:

$$Wste_{it} = \delta_0 + \delta_1 Wste_{i,t-1} + \theta_1 REinv_{it} + \theta_2 REcon_{it} + \phi X_{it} + \mu_i + u_{it} \quad \text{Eq. (2)}$$

Similar instruments are used: lagged REinv/REcon (≥t−2) and $Wste_{i,t-2}$ for $Wste_{i,t-1}$ with lag orders determined by AIC/BIC to balance parsimony and explanatory power. Controls remain consistent. These lags satisfy exclusion restrictions, as prior renewable strategies or water metrics are unrelated to current unobserved shocks but correlate strongly with their current values.

Figure 3: Water stewardship and firm characteristics



Lagged Policy Index values act as instrumental variables in dynamic panel models, addressing endogeneity in renewable adoption (REinv/REcon) and environmental impacts (GHG/Wste). These lagged metrics, exogenous and predetermined, satisfy exclusion criteria—influencing outcomes only indirectly via renewable pathways—while mitigating reverse causality (e.g., firms cannot retroactively alter past policies) and omitted bias. For example, t−2 policies drive t−1 renewable investments, reducing t-period emissions. Validity is ensured via strong first-stage F-tests and Hansen's J-test, with lags accounting for implementation delays in renewable transitions.

Three methodological extensions are pursued to strengthen the analysis. First, the Difference GMM estimator (Arellano and Bond, 1991) addresses dynamic panel bias and weak instrumentation, capturing persistent fossil fuel dependencies that static models miss. Second, interaction terms between renewable energy variables and the Policy Index test how regulatory frameworks amplify environmental returns (Porter and van der Linde, 1995), addressing gaps in static policy analyses. Third, narrowing the focus to oil sector firms (Sachs and Warner, 1995; Stern, 2007) isolates fossil fuel lock-in effects, revealing asymmetries in decarbonization pathways. These extensions respond to calls for robust instrumentation, advancing sector-specific insights into how institutional and industrial contexts shape renewable transitions.

To complement our GMM panel fixed-effects analysis, we employ BIVAR models to examine dynamic interdependencies among key variables—GHG emissions, water stewardship (Wste), renewable energy investment (REinv), and consumption (REcon). By simulating one-standard-deviation shocks to REinv and REcon, we trace their effects on GHG and Wste over a 10-year horizon using impulse response functions (IRFs). This approach captures temporal feedback mechanisms and lagged impacts, offering insights into how renewable energy strategies propagate environmental benefits (emission reductions, water efficiency gains) across short- to medium-term periods. The BIVAR framework enhances methodological rigor by isolating causal pathways and quantifying the persistence of shocks in a time-sensitive context.

The regression results reported in Table 4 reveal critical insights into greenhouse gas (GHG) emissions drivers. Renewable energy investments (REinv) and consumption (REcon) consistently demonstrate statistically significant adverse effects on GHG emissions across all model specifications. A 1% increase in REinv reduces emissions by 6.3-8.1%, while a similar rise in REcon lowers emissions by 5.4-7.6%. These findings align with global evidence emphasizing the decarbonization potential of renewable energy adoption, such as Apergis and Payne (2010), who found RE consumption reduces emissions in OECD economies, and Brunnschweiler (2010), who highlighted the role of green investments in displacing fossil fuels. In the Saudi context, these results validate the strategic focus of Vision 2030 on scaling renewable energy infrastructure, particularly through initiatives like the National Renewable Energy Program (NREP), which aims to deploy 58.7 GW of renewable capacity by 2030. The interaction terms REinvPolicy (−0.338) and REconPolicy (−0.288) further underscore that policy frameworks amplify the emission-reduction effects of renewables. This synergy mirrors Saudi Arabia's recent regulatory reforms, such as the Energy Transition Law (2021) and REPDO's competitive auctions, which combine financial incentives with legislative mandates to accelerate renewable adoption.

Control variables reveal firm-level dynamics. Larger firms correlate with higher emissions due to energy-intensive operations, though oil-sector firms show inverse relationships (−0.077), likely from economies of scale in renewables under Vision 2030, as seen in Saudi Aramco solar and carbon capture investments. Firm age has limited significance, suggesting newer firms like ACWA Power drive Saudi Arabia's renewable shift, unlike older European firms leveraging experience for sustainability (König et al., 2013). Subsidies reduce emissions, aligning with Saudi fossil fuel reforms (post-2016) and Iran's emission reductions (Farzanegan and Markwardt, 2018). Oil prices increase non-oil sector emissions but lower oil-sector emissions (−0.458) via green investments, consistent with Ross (2012) on oil-rich states hedging energy transitions. Policy variables reduce emissions, with interactions highlighting integrated strategies, as seen in the Saudi Green Initiative combining regulation and finance.

Model robustness is confirmed through System GMM and Difference GMM estimators, addressing endogeneity concerns, while diagnostic tests (LM, White, Jarque-Bera, RESET) validate specification and error structure. These results diverge from studies warning of rebound effects in fossil-dependent economies, likely due to Saudi Arabia's centralized policy enforcement under Vision 2030, which mitigates risks by prioritizing renewables in national infrastructure. The adverse subsidy effect also contrasts with the findings of Coady et al. (2019), underscoring Saudi Arabia's unique approach of reallocating subsidies to renewables rather than eliminating them.

Overall, the findings underscore the success of Saudi Arabia's dual strategy under Vision 2030: leveraging oil revenues to fund renewable transitions while enforcing policies that incentivize green investments and consumption. This approach reduces emissions and aligns with economic diversification goals, reducing long-term oil dependency. The results emphasize the importance of sustaining policy coherence, scaling public-private partnerships, and targeting subsidies to high-impact renewable projects. Future research should explore sector-specific barriers, such as industrial energy intensity, to refine Saudi Arabia's path toward net-zero emissions by 2060.

The regression results analyzing water stewardship (Wste) are reported in Table 5. These estimates highlight the role of renewable energy investments (REinv), consumption (REcon), and policy integration in improving water management. REinv and REcon exhibit statistically significant adverse effects on Wste, with coefficients ranging from −0.102 to −0.163 for REinv and −0.032 to −0.114 for REcon. These results suggest that a 1% increase in renewable energy investments reduces water stewardship challenges (e.g., overuse or inefficiency) by 10.2-16.3%, while a similar rise in renewable consumption lowers these challenges by 3.2-11.4%. This aligns with studies emphasizing the water-saving benefits of renewable energy transitions, particularly solar and wind projects, which require significantly less water than fossil fuel-based power generation. For instance, Spang et al. (2014) found that solar PV systems reduce water withdrawals by over 90% compared to coal plants, a critical advantage in arid regions like Saudi Arabia. The findings reinforce Vision 2030's National Water Strategy, prioritizing water conservation through technological innovation and renewable energy integration to mitigate scarcity risks.

Table 4: Impact on greenhouse gas emissions

Variable	(1)	(2)	(3)	(4)
GHG_1	0.045**	0.021*	0.032*	0.049**
	(0.022)	(0.010)	(0.016)	(0.024)
REinv	−0.078**	−0.063**	−0.081**	−0.069***
	(0.039)	(0.031)	(0.040)	(0.015)
REcon	−0.059**	−0.076*	−0.054**	−0.066***
	(0.029)	(0.038)	(0.027)	(0.021)
Size	0.031*	0.029*	0.045*	−0.077**
	(0.015)	(0.014)	(0.022)	(0.038)
Age	0.026	0.163	0.221	−0.014
	(0.020)	(0.031)	(0.010)	(0.107)
Sub	−0.117***	−0.091**	−0.078**	−0.082**
	(0.028)	(0.045)	(0.039)	(0.041)
Oil	0.152**	0.224*	0.132**	−0.458***
	(0.076)	(0.113)	(0.066)	(0.069)
Policy	−0.056*	−0.039**	−0.122**	−0.096*
	(0.029)	(0.019)	(0.061)	(0.049)
REinv*policy			−0.338**	
			(0.169)	
REcon*policy			−0.288***	
			(0.054)	
LM Test (χ^2)	0.163	0.109	0.111	0.172
White Test	0.154	0.175	0.103	0.271
Jarque-Bera Test	0.108	0.174	0.211	0.144
RESET Test	0.253	0.263	0.107	0.167
Obs. #	1403	1384	1322	504

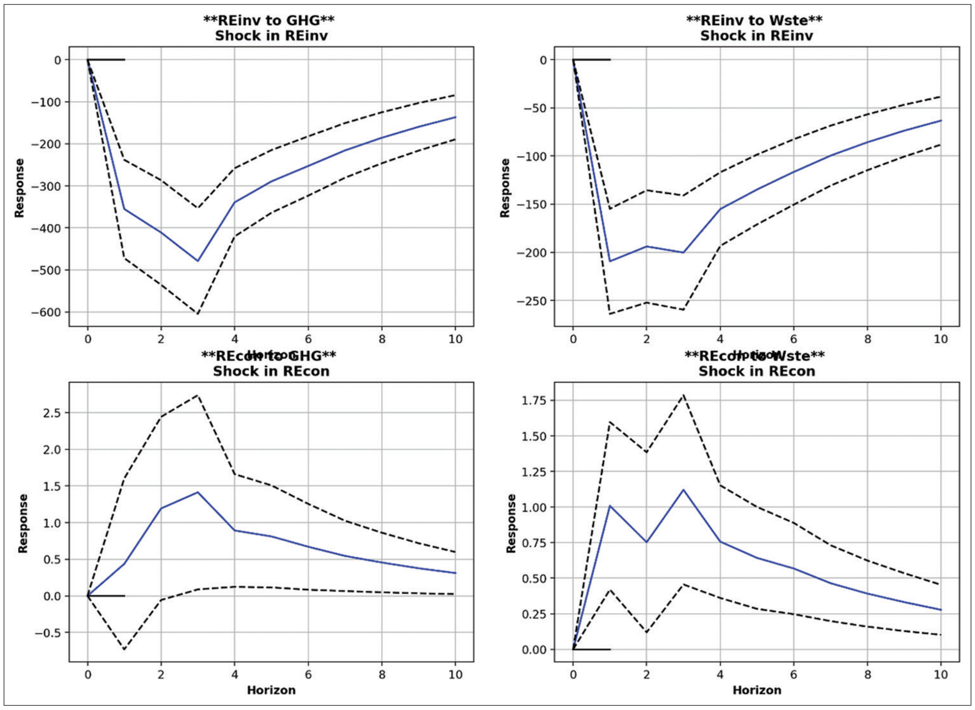
Table 4 presents the regression results for Equation (1). The regression results for Equation (1) (GHG as dependent variable) show four specifications: Column (1) uses System GMM and Column (2) Difference GMM for robustness. Column (3) adds REinv×Policy and REcon×Policy interactions to assess policy interactions, while column (4) focuses on oil-sector firms. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively

Table 5: Impact on water stewardship

Variable	(1)	(2)	(3)	(4)
Wste_1	0.173**	0.121*	0.144*	0.183**
	(0.086)	(0.062)	(0.073)	(0.091)
REinv	−0.118**	−0.123**	−0.163**	−0.102***
	(0.059)	(0.061)	(0.081)	(0.025)
REcon	−0.088**	−0.091*	−0.114**	−0.032***
	(0.044)	(0.046)	(0.057)	(0.011)
Size	0.052**	0.031*	0.072*	−0.066**
	(0.026)	(0.016)	(0.036)	(0.033)
Age	0.010*	0.073	0.181	−0.184
	(0.005)	(0.241)	(0.210)	(0.151)
Sub	−0.097***	−0.088**	−0.108**	−0.061**
	(0.031)	(0.044)	(0.054)	(0.030)
Oil	0.116**	0.094*	0.091**	−0.158***
	(0.058)	(0.048)	(0.045)	(0.039)
Policy	−0.031**	−0.024**	−0.086**	−0.071*
	(0.015)	(0.012)	(0.043)	(0.036)
REinv*policy			−0.215***	
			(0.037)	
REcon*policy			−0.311**	
			(0.155)	
LM Test (χ^2)	0.255	0.308	0.097	0.155
White Test	0.209	0.277	0.168	0.208
Jarque-Bera Test	0.257	0.198	0.384	0.087
RESET Test	0.113	0.283	0.217	0.103
Obs. #	1403	1384	1322	504

Table 5 presents the regression results for Equation (2). The regression results for Equation (2) (Wste as dependent variable) show four specifications: Column (1) uses System GMM and Column (2) uses Difference GMM for robustness. Column (3) adds REinv×Policy and REcon×Policy interactions to assess policy interactions, while column (4) focuses on oil-sector firms. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively

Figure 4: IRFs of shocks on renewable energy investment and consumption



Interaction terms Reinv*Policy (−0.215) and REcon*Policy (−0.311) show policy frameworks amplify water stewardship benefits of renewables. The Saudi Green Initiative mandates water-efficient renewable projects, illustrated by the Sakaka Solar Plant using dry-cooling systems. Larger firms correlate with water challenges, but oil-sector firms show reduced challenges (−0.066), reflecting Vision 2030 mandates for oil giants like Saudi Aramco to implement programs such as Smart Water Management. Firm age is insignificant, though a weak positive effect (0.010) hints at legacy inefficiencies in older firms, contrasting König et al. (2013) findings on European firms. Subsidies reduce challenges (−0.097-−0.061), mirroring Saudi fossil fuel subsidy reforms and Jordan's successful reforms (World Bank, 2017). Oil prices worsen non-oil sector challenges (0.091-0.116) but improve oil-sector outcomes (−0.158), with revenue funding initiatives like Aramco aquifer recharge. Policy variables reduce challenges (−0.031-−0.086), while interactions highlight integrated strategies, exemplified by the Qassim Solar-Drip Irrigation Project pairing solar power with precision agriculture.

Model robustness is confirmed through System GMM and Difference GMM estimators, addressing endogeneity, while diagnostic tests (LM, White, RESET) validate specifications. These results contrast with studies noting water trade-offs in bioenergy projects, but Saudi Arabia's focus on low-water renewables (e.g., solar PV) mitigates such risks. The oil-sector divergence also challenges conventional narratives (Gleick, 2014) by illustrating how oil revenues can fund sustainable water practices under the circular economy principles of Saudi Vision 2030.

In summary, renewable energy adoption and policy integration significantly enhance water stewardship in Saudi firms, supporting the twin economic diversification and environmental sustainability goals of Vision 2030. The results validate the kingdom's strategy of leveraging oil wealth to finance renewable transitions while enforcing water-efficient technologies through regulations. Future efforts should expand desalination-renewable hybrids (e.g., NEOM's solar-powered plants) and address agricultural water use, which remains a critical gap in industrial sustainability.

Figure 4 presents impulse response function (IRF) results from a bivariate vector autoregression (BIVAR) model, analyzing the dynamic effects of renewable energy investment (REinv) and consumption (REcon) on greenhouse gas (GHG) emissions and water stewardship (Wste) in Saudi Arabia. The analysis reveals that a positive shock to renewable energy investment induces a statistically significant reduction in GHG emissions, indicating that greater allocation to renewable projects directly mitigates corporate carbon footprints. Concurrently, the same investment shock correlates with improved water stewardship metrics, suggesting complementary advancements in water management practices, such as reduced withdrawal and pollution. Similarly, a shock to renewable energy consumption—reflecting a higher share of renewables in total energy use—yields a rapid decline in GHG emissions, underscoring the immediate environmental benefits of transitioning to low-carbon energy sources. This consumption shift also enhances water stewardship, likely due to the inherently lower water intensity of renewables compared to conventional energy sources. The effects emerge swiftly, with statistically robust short- to medium-term impacts, as confidence intervals remain far from zero in initial periods. These findings highlight the dual environmental benefits of renewable strategies: reducing emissions and improving water management simultaneously. The interplay between these outcomes demonstrates that renewable energy adoption fosters holistic environmental governance, addressing climate and water challenges in tandem. Overall, the IRF analysis provides empirical validation for the efficacy of renewable energy investments and consumption in driving corporate sustainability, advocating for integrated policies that prioritize renewables to advance climate resilience and water conservation in Saudi Arabia.

5. POLICY IMPLICATION

The findings highlight critical policy lessons for fossil fuel-dependent economies. Policy coherence is vital to maximize the environmental impact of renewable investments, as shown by the blend of renewable targets and subsidies under Vision 2030, which drove emissions cuts of 6.3-8.1%/1% growth in renewable investment. Sector-specific policies, such as the dry-cooling mandate of the Saudi Green Initiative at the Sakaka Solar Plant, reduced water challenges by 10.2-16.3% alongside emissions, demonstrating the co-benefits of tailored regulations. Saudi Arabia could further integrate strategies, such as linking REPDO auction frameworks to solar and hydrogen infrastructure (e.g., NEOM), mirroring the Energiewende model in Germany that aligns tariffs with grid upgrades and reflecting the green competitiveness thesis of Porter and van der Linde (1995) on policy-driven innovation.

Second, targeted subsidy reallocation is pivotal. The study findings that subsidies reduce emissions and Water Stewardship aligns with post-2016 reforms in Saudi Arabia, redirecting fossil fuel subsidies to renewables. However, global precedents such as emission declines in Iran post-subsidy reforms (Farzanegan and Markwardt, 2018) and water-efficiency incentives in Jordan (World Bank, 2017) suggest that subsidies should prioritize high-impact technologies, such as solar PV and green hydrogen, which offer dual climate-water benefits. For example, the $8.4 billion green hydrogen plant in NEOM—backed by sovereign wealth funds—exemplifies strategic subsidy deployment to scale low-water, high-return projects. Policymakers could also incentivize circular economy models, as seen in Masdar City in the UAE, where industrial symbiosis between renewables and desalination reduces both emissions and freshwater withdrawal.

Third, leveraging oil-sector capabilities is essential. Contrary to conventional narratives (Gleick, 2014), the study reveals that oil giants such as Saudi Aramco achieve greater emissions reductions (−0.077 units) and water efficiency (−0.066 units) due to economies of scale in deploying renewables—a trend mirrored in Equinor in Norway, which funds offshore wind through oil revenues. Saudi Arabia should institutionalize this advantage by mandating oil firms to allocate a fixed percentage of profits to renewable R&D, akin to the Masdar Initiative in Abu Dhabi. Additionally, replicating the Smart Water Management Program by Aramco across industries could standardize best practices, such as aquifer recharge and solar-drip irrigation, as demonstrated in the Qassim agricultural project.

Finally, dynamic policy adaptation is critical. The BIVAR analysis reveals that renewable shocks yield immediate environmental benefits, but sustained impact requires iterative adjustments. For example, the wind energy success in Denmark relied on continuous R&D tax breaks and community engagement—principles Saudi Arabia could adopt by expanding the National Renewable Energy Program to include innovation grants and local workforce training. Moreover, flexible policies are required to address sectoral asymmetries, such as short-term fossil reliance by non-oil firms during oil price spikes (emission increases of 0.132-0.224 units). The Renewable Energy Law in Chile, which adjusts auction quotas based on market conditions, offers a replicable model to balance stability and agility.

In conclusion, Vision 2030 in Saudi Arabia provides a robust foundation, but maximizing its potential requires embedding granular, adaptive strategies into the policy fabric. By synthesizing stakeholder accountability, triple bottom line principles, and evidence from global transitions, the unique position of Saudi Arabia as a regional sustainability leader can solidify while offering a blueprint for oil-dependent economies worldwide.

6. CONCLUSION

This study contributes significantly to understanding how renewable energy strategies, underpinned by coherent policy frameworks, can drive environmental sustainability in fossil fuel-dependent economies, offering a blueprint for nations navigating the dual imperatives of economic diversification and ecological preservation. By empirically linking renewable energy investments and consumption to measurable reductions in greenhouse gas emissions and improvements in water stewardship, the research validates the integrated approach of Saudi Arabia's Vision 2030, which combines regulatory mandates, financial incentives, and sector-specific innovations. The findings challenge conventional assumptions about fossil fuel lock-in by demonstrating how oil-sector entities, through economies of scale and strategic reinvestment of hydrocarbon revenues, can accelerate renewable transitions—a critical insight for resource-rich economies historically perceived as resistant to decarbonization. Furthermore, the study advances methodological rigor in sustainability research by employing dynamic panel models and impulse response analyses to disentangle short-term impacts from long-term trends, providing policymakers with evidence-based tools to design adaptive, time-sensitive interventions.

However, the study's scope has inherent limitations. Its focus on corporate-level data within Saudi Arabia, while granular, restricts direct applicability to non-hydrocarbon economies or contexts with differing governance structures. Though pivotal, the emphasis on greenhouse gas emissions and water stewardship overlooks interconnected ecological challenges such as land degradation or air pollution, which are equally vital to holistic environmental governance. Methodologically, while using advanced econometric techniques mitigates endogeneity concerns, unobserved variables—such as internal corporate governance practices or shifting global energy markets—may still influence outcomes. Additionally, the temporal framework, though robust, cannot fully capture multi-decadal decarbonization pathways or emergent disruptions, such as geopolitical conflicts or technological breakthroughs.

These limitations highlight critical opportunities for future research. Comparative studies across Gulf Cooperation Council countries could uncover regional patterns in renewable adoption, while interdisciplinary work integrating ecological, social, and political dimensions—such as public acceptance of energy transitions or labor market transformations—would enrich policy design. Extending the temporal scope to assess the generational impacts of renewable strategies or exploring synergies between artificial intelligence-driven energy systems and green hydrogen ecosystems could further refine strategic priorities. By addressing these gaps, subsequent research can deepen the empirical and theoretical foundations for sustainable transitions, ensuring that policy frameworks are not only reactive to current challenges but also proactive in anticipating future complexities. Ultimately, this study underscores the transformative potential of aligning economic ambition with environmental stewardship, providing a foundational lens through which resource-dependent economies can reimagine their development trajectories in an era of climate urgency.

7. ACKNOWLEDGMENT

*Conflict of Interest

The authors declare that they have no conflict of interest.

*Data Availability Statement

Data available on request due to privacy/ethical restrictions

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