



The Impact of Resource Efficiency on Energy Intensity and Sustainability

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ABSTRACT

Energy intensity (EI) is a crucial metric for assessing sustainable economic performance, but its understanding and effectiveness remain subject to discussion. In the context of South Africa's water-energy-food (WEF) nexus, this study empirically investigates the relationship between resource efficiency and energy intensity (EI), highlighting the transitional dynamics of the country's Just Energy Transition. The study examines the short- and long-term impacts of water productivity (LWP), water withdrawal intensity (LWWI), electricity production from renewable sources (EPRS), and cereal yield (CY) on energy intensity using the autoregressive distributed lag (ARDL) approach and annual time-series data covering 1990-2023. The results show that these variables have a statistically significant long-term cointegrating relationship. A higher energy intensity is linked to both short- and long-term increases in renewable electricity generation, which reflects transitional inefficiencies in early-stage renewable integration. On the other hand, reductions in water withdrawal intensity dramatically reduce energy intensity, highlighting the significance of water-use efficiency in reducing pressures on energy demand. The statistically insignificant effects of agricultural yield and water productivity point to structural heterogeneity and compensatory mechanisms in South Africa's resource systems. The results indicate that the just transition needs to consider the shifting trade-offs between efficiency and decarbonization, necessitating social inclusion, institutional collaboration, and technological advancements. Policy implications include boosting inter-sectoral governance mechanisms, encouraging water-efficient technologies, and improving grid flexibility. Quantifying resource interdependencies that influence sustainable energy transitions in emerging economies adds to the empirical discussion of the WEF nexus.

Keywords: Energy Intensity, Water-Energy-Food Nexus, Renewable Energy, Water Efficiency, Cereal Yield, Autoregressive Distributed Lag Model, South Africa

JEL Classifications: O16, E44, G21

1. INTRODUCTION

Energy intensity (EI) is a crucial metric for assessing sustainable economic performance, but its understanding and effectiveness remain subject to discussion. Research shows that economic efficiency is positively linked to R&D expenditure and technological export rates, while contributing to a reduction in energy intensity consumption (Bojnec and Papler, 2011). However, traditional EI evaluations can be misleading when evaluating progress in sustainability. Since developing nations exhibit enduring coupling

trends, the global decoupling of energy and growth is less evident when examining population size using energy/GDP per capita ratios (Bithas et al., 2020). Due to their historical backgrounds and developmental stages, European economies show various energy-growth relationships; after 1990, economic growth became more susceptible to changes in energy prices (Gulzar et al., 2022). Critics argue that EI metrics are often discussed without sufficient scrutiny in policy debates, potentially misleading policymakers by conflating efficiency with intensity and promoting unrealistic hopes for decoupling (Rodríguez et al., 2020).

South Africa confronts a complicated dual dilemma of attaining energy efficiency while sustaining economic growth, as its economy is significantly energy-intensive and primarily driven by raw material extraction and primary processing (Nkomo, 2005). Studies indicate a one-way causal relationship among energy efficiency, non-renewable energy use, and economic development, implying that energy efficiency is an important mechanism for promoting sustainable growth while meeting climate targets (Enock Gava et al., 2025). The government has created extensive policy frameworks, such as the national energy efficiency strategy, aiming for a 12% decrease in final energy demand by 2015, prioritizing energy efficiency as a vital route to low-carbon development (Nhamo and Bimha, 2011). Translating policy into action poses substantial difficulties, necessitating intricate connections among supporting laws, institutional frameworks, funding sources, and collaborative governance to guarantee that climate change mitigation and energy security bolster the development agenda while not undermining economic growth (Rosenberg and Winkler, 2011).

The water-energy-food (WEF) nexus framework has become an essential strategy for tackling resource interconnections and fostering sustainability transitions. The nexus idea highlights the significance of cohesive resource management to address conventional “silo” methods that lead to development shortcomings and heightened vulnerabilities (Nhamo et al., 2018). Resource efficiency analysis shows considerable differences in performance across countries, with OECD countries averaging efficiency scores between 68% and 78%, indicating significant potential for enhancement (Ibrahim et al., 2019). The framework is especially significant for attaining fair energy transitions harmonizing economic development, environmental sustainability, and social equity (Li and Zhang, 2023). Environmental sustainability demands a comprehensive examination of the WEF nexus, as the utilization of resources in one sector significantly impacts others, requiring increased social awareness, the implementation of renewable energy, and improved efficiency strategies (Zarei et al., 2020). Effective execution requires collaboration across sectors, aligned policies, and cutting-edge technologies to enhance resource coordination and management.

Despite increasing renewable energy and reforms in the water sector, South Africa still faces consistently elevated energy intensity. Global experiences highlight the intricacy of this phenomenon. In Gujarat, India, reforms in the water and energy sectors effectively encouraged micro-irrigation systems and set up distribution companies (DISCOMs). Nevertheless, obstacles persist in attaining sustainable water and energy security due to rising inter-sectoral competition (Viswanathan et al., 2022). The energy-water connection adds extra complexity, as policy disarray across sectors results in trade-offs that may weaken efficiency improvements, like energy-demanding desalination facilities and groundwater extraction (Hussey and Pittock, 2010).

Worldwide, the advancement of renewable energy decreases energy intensity, though the extent of the impact differs greatly depending on the level of development. Nations that utilize significant renewable energy (>10.58 billion MJ) experience a

2.2% decrease in intensity for every 10% rise in renewables, whereas low-development countries see just 0.2% (Yu et al., 2022). In developing and emerging economies, demographic elements like workforce participation may counteract renewable energy advancements, leading to higher energy intensity unless accompanied by structural and technological changes (Suparta et al., 2025). These results underscore the necessity for a holistic and unified policy strategy that tackles technological changes and the socio-economic and demographic aspects of the energy transition (David et al., 2024).

Significant knowledge deficiencies exist in South Africa concerning the relationship among water efficiency, agricultural output, and energy consumption. Mabhaudhi et al. (2018) emphasize that enhancing water productivity in irrigated agriculture could lower water and energy consumption while boosting yields. However, there is still uncertainty about the appropriate redistribution of these savings. The authors highlight the necessity of cohesive planning strategies to prevent the shifting of issues across sectors. Khofi et al. (2025) highlight an important shortcoming in comprehending the interplay of socioeconomic and environmental factors in South Africa’s WEF nexus, especially concerning resource distribution disparities. Ololade (2018) also highlights the mutual reliance of the water and energy sectors, as coal-driven energy generation demands significant water resources in areas with limited water availability. Mutanga et al. (2024) note that although there are many studies on the WEF nexus, there is still a lack of empirical understanding regarding the factors that help or hinder nexus implementation, particularly when health aspects are included. This lack of understanding is worsened by a disjointed policy framework in numerous African countries, whereby uncoordinated governance in water, energy, and food sectors frequently results in poor resource distribution and compromises that hinder sustainable development (Cho et al., 2024).

This study seeks to:

- Assess resource efficiency elements such as log of water productivity (LWP), log of water withdrawal intensity (LWWI), electricity production from renewable sources (EPRS), and cereal yield (CY), which affect energy intensity in South Africa
- Examine both short and long-run dynamics by employing the ARDL model.

This study adds to the expanding empirical body of work on the water-energy-food (WEF) nexus and its effects on sustainable energy transitions in developing economies. These economies struggle to align developmental needs with climate obligations, striking a balance between energy accessibility and decarbonization objectives (Ahuja and Tatsutani, 2009). Studies show that focused policy measures can significantly speed up sustainable energy transitions, as strategic initiatives tend to be more effective than regulatory laws in encouraging electrification and the use of renewable energy. Simultaneously, legal tools significantly improve energy efficiency (Chen et al., 2022).

A thorough framework for sustainable energy transitions highlights the importance of incorporating renewable energy,

enhancing efficiency, and diversifying funding methods while tackling institutional fragmentation and technical limitations (Giwah et al., 2020). Achieving success demands flexible policies, tailored economic incentives, and improved global collaboration (Ibrahim, 2024). Therefore, linking sustainable energy policy with broader socioeconomic development objectives is essential for attaining a Just Transition that promotes environmental integrity and social equity.

2. LITERATURE REVIEW

2.1. Theoretical Framework: The Water–Energy–Food (WEF) Nexus

Studies on energy intensity and resource efficiency frameworks uncover intricate mechanisms driving energy usage behaviors and shifts toward sustainability. The theoretical foundation for comprehending variations in energy intensity stems from structural change models that link energy intensity dynamics to shifts in sectors and technological developments. Cao (2017) presents an advanced structural change model illustrating that changes in overall energy intensity of the economy are affected by structural transformations and alterations in sectoral energy efficiency, with the rates of technological advancement and substitution elasticities influencing whether energy intensity changes in a consistent manner or exhibits non-linear (U-shaped or inverted-U) paths.

Kander et al. (2020) broaden this analysis by questioning the belief that advancements in energy efficiency invariably lead to decreased energy consumption. Based on Jevons' Paradox, they contend that rebound effects, where efficiency improvements reduce the actual cost of energy and encourage further consumption, might lead to minimal overall energy savings. These writers emphasize the ongoing impact of infrastructure inertia and capital stock rigidity as key factors influencing long-term energy intensity results, pointing out that the offshoring of energy-intensive manufacturing via international trade has a relatively minor effect on national energy intensity patterns. Moreover, although energy-development and environmental policies have traditionally been out of sync, their combination is essential for attaining sustainable development goals, especially in reconciling energy security with environmental protection (Lv, 2023).

In addition to structural and rebound theories, ecological modernization and environmental transition frameworks account for changes in energy intensity within broader socio-technical transformations. Shah et al. (2020) utilize these frameworks to illustrate a U-shaped relationship among carbon emissions, urbanization, and income per capita, indicating that initial phases of industrialization heighten energy consumption. In contrast, later phases might produce decoupling effects as cleaner technologies and more stringent environmental regulations arise. Their results highlight that urban growth, financial progress, and institutional advancement have positive but intricate impacts on energy intensity, influenced by technological and behavioral adjustment processes. These theories indicate that although advancements in technology and changes in economic structure can enhance energy efficiency, their overall effect on energy use is frequently influenced by intricate feedback processes, such as the rebound

effect and socio-economic shifts (Kazemzadeh et al. 2024; Gebara & Laurent, 2023; Huang & Ren, 2024).

On the broader sustainability conversation, resource efficiency has emerged as a fundamental element of environmental policy structures and the WEF nexus strategy. In evaluating the European Union's Resource Efficiency Roadmap, Flachenecker (2015) finds that while it partially complies with sustainability objectives, social and institutional factors are not sufficiently considered. The empirical analysis also shows that resource efficiency had little impact on competitiveness from 2004 to 2009, indicating a gap between policy objectives and actual economic results. Conversely, Chen et al. (2023) demonstrate that effective resource management in Chinese provinces considerably lowers carbon intensity, while urban growth and industrial development undermine these advantages by increasing fossil fuel use. Their research highlights that incorporating circular economy concepts, utilizing renewable energy, and enhancing resource efficiency can establish collaborative routes for decarbonization.

At the microeconomic level, Majid et al. (2023) show that eco-efficiency strategies—like energy saving, using renewable energy, and reducing waste—beneficially affect business performance in European SMEs, even with a lack of awareness regarding financial gains. Similarly, Bojnec and Papler (2011) validate that economic efficiency is closely linked to R&D spending and the intensity of technological exports, leading to a decrease in total energy consumption. These studies emphasize that technological progress, institutional collaboration, and policy consistency are crucial for resource efficiency and sustainable energy transformations. These transitions are made more complex by the relationship between energy efficiency and energy conservation, which, while different, are both essential for reducing environmental impacts and improving economic competitiveness (Mushafiq et al., 2023).

From a nexus viewpoint, the interconnections between water, energy, and food systems significantly impact sustainability results. The WEF nexus framework suggests that actions in one resource area can produce cascading impacts, synergies, or trade-offs in the others. Water is essential for generating energy and producing food; energy is needed for the extraction, treatment, and irrigation of water; food production influences the demand for water and energy. This connection suggests that inefficiencies in one area can worsen shortages in another, threatening overall resource stability. According to Nhamo et al. (2018) and Li and Zhang (2023), implementing integrated management strategies within the WEF nexus can alleviate these risks by maximizing resource distribution, fostering fairness, and improving resilience. This systems-oriented viewpoint offers the theoretical basis for examining how water and agricultural efficiency factors affect energy intensity in South Africa.

2.2. Empirical Studies on Energy Intensity

Empirical studies on the factors affecting energy intensity show that the adoption of renewable energy, efficiency in water use, and agricultural productivity have distinct but interrelated effects depending on regional and developmental circumstances. Renewable energy is generally recognized for reducing greenhouse

gas emissions and enhancing environmental performance, though its impact on energy intensity may differ over time and across different regions. Majeed (2019) shows that renewable energy sources like solar, wind, geothermal, and hydroelectric power help reduce emissions, while water extraction raises emissions because of energy-demanding extraction and treatment processes. Siddiqi and Fletcher (2015) emphasize that water utilization shows notably high energy intensity in agriculture, with groundwater extraction constituting the majority of farm energy consumption. Irrigation systems that aim to conserve water can lead to higher energy consumption, underscoring the existence of resource trade-offs in the WEF nexus.

On a global scale, Fuglie et al. (2024) indicate that enhancements in agricultural productivity are inversely related to emissions intensity, noting that global agricultural emissions intensity has fallen by more than 50% since 1990. Areas that saw increased productivity growth also had larger reductions in emissions intensity, indicating that advancements in technology and efficiency in agriculture help to ease energy intensity challenges. Napoli and Tellez (2016) emphasize that sustainable agricultural production necessitates a comparative assessment of water productivity and energy needs, as inefficiencies in one resource area affect the others. This underscores the essential requirement for unified nexus-oriented approaches considering these interconnected dependencies to enhance resource use and attain sustainable results (Ningi et al., 2025).

Analyses specific to regions highlight the intricacy of these interactions. In the ASEAN area, Chopra et al. (2022) highlight a reciprocal link between renewable energy consumption and agricultural output. This shows that the growth of renewables boosts agricultural production, while increased productivity drives energy consumption. Daraz et al. (2025) demonstrate that innovative solar-powered irrigation systems in Pakistan's Cholistan Desert increased yields from 3.0 to 4.8 tons/ha while decreasing water and energy use, affirming that technological advancements can achieve beneficial efficiency results. In contrast, Liu (2016) discovers that energy intensity shows considerable variation among California's hydrological regions due to climate variability, with climate change exacerbating WEF nexus stresses and diminishing the predictability of ecosystem service flows.

In Sub-Saharan Africa (SSA), empirical data show similarly intricate and frequently conflicting relationships. Aboagye and Alagidede (2016) demonstrate that efficiency in energy consumption in SSA correlates positively with trade liberalization and local price adjustments, with agricultural sectors exceeding industrial and service sectors in energy efficiency measures. Nonetheless, Ramachandran (2021) contends that structural change throughout Africa requires significant energy-demanding investments in infrastructure—especially in fertilizer manufacturing, water management, and storage systems—to boost agricultural efficiency. Dimnwobi et al. (2022) also note that energy poverty has varied impacts on agricultural productivity throughout SSA, as rural electrification enhances output while ecological degradation, assessed by ecological footprint, limits productivity.

In southern Africa, the WEF nexus highlights both limitations and prospects for sustainability. Mabhaudhi et al. (2018) indicate that agriculture makes up 70% of regional water extraction, while increasing irrigation needs heighten energy demands. Consequently, integrated planning and intersectoral collaboration are vital to manage conflicting resource demands. South Africa, Sparks et al. (2013) show that thermoelectric power plants have significant water needs, especially those using wet-cooling systems. In contrast, photovoltaic and wind energy systems exhibit minimal dependence on water, which makes them suitable for regions with scarce water resources. Nonetheless, Tagwi (2023) notes that the short-term economic impacts of renewable energy expansion on agricultural development might be harmful, as reallocating financial and energy resources to renewable infrastructure momentarily obstructs agricultural productivity.

System-level modeling indicates that South Africa's resource management is only slightly sustainable (Nhamo et al., 2020). Through system dynamics simulations, Nanfuka and Oosthuizen (2023) demonstrate that the interrelatedness of the water and energy sectors, exacerbated by the nation's semi-arid climate, generates feedback loops that intensify resource stress given the existing policy framework. These studies emphasize the necessity for comprehensive econometric modeling to measure the relationships among renewable energy, water efficiency, and agricultural productivity and their collective impact on energy intensity. This study seeks to fill this analytical void by creating an econometric model to evaluate how these interconnections affect energy intensity in South Africa, a country grappling with significant issues in the WEF nexus (David et al., 2024).

2.3. Research Gap

Although there is extensive literature on the water–energy–food (WEF) nexus and energy transitions, empirical studies incorporating WEF indicators into econometric frameworks are still lacking, especially in South Africa. Present studies often utilize descriptive or systems-dynamics approaches without formally evaluating causal relationships between resource efficiency indicators and energy intensity. This limits the ability to develop policy suggestions grounded in evidence. Moreover, while incorporating renewable energy is vital for South Africa's energy transition strategy, current research neglects transitional inefficiency periods where the increase of renewables briefly elevates energy intensity due to infrastructural, technological, and institutional constraints (Sovacool, 2009).

Consequently, this study addresses two primary shortcomings. It improves empirical understanding by combining multiple WEF-related efficiency metrics, such as log of water productivity (LWP), log of water withdrawal intensity (LWWI), electricity production from renewable sources (EPRS), and cereal yield (CY), into an ARDL econometric framework. Additionally, it examines the patterns of energy intensity both in the short term and long term to assess the impact of transitional inefficiencies and resource connectivity on sustainability outcomes in South Africa. This cohesive framework enhances comprehension of resource efficiency and delivers policy-relevant insights for

attaining a Just Transition that harmonizes economic resilience with environmental goals.

3. DATA AND METHODOLOGY

3.1. Model Specification

This study uses an autoregressive distributed lag (ARDL) modeling approach to examine the dynamic connection between resource efficiency and energy intensity in South Africa. It explicitly analyzes the immediate and extended impacts of water and agricultural efficiency variables and renewable electricity production on energy intensity (EI). The overall functional connection is articulated as follows:

$$\Delta EI_t = f(\Delta LWP_p, \Delta LWWI_p, \Delta EPRS_p, \Delta CY_t)$$

Where:

- EI = Energy Intensity (energy use per unit of GDP)
- LWP = Log of Water Productivity (economic output per unit of water used)
- LWWI = Log of Water Withdrawal Intensity (water use relative to GDP)
- EPRS = Electricity Production from Renewable Sources (% of total electricity generation)
- CY = Cereal Yield (kg per hectare).

The model is based on the water–energy–food (WEF) nexus framework, highlighting the interconnectedness of resource utilization efficiency among essential sectors. Water productivity (LWP) improvements are anticipated to decrease energy intensity by increasing economic yield per unit of water used, aligning with Sarkodie and Adams’s empirical results (2018). On the other hand, greater water withdrawal intensity (LWWI) suggests ineffective water utilization or pressure on infrastructure, potentially increasing energy demands for extraction, treatment, and distribution (Chen et al., 2020).

Electricity generation from renewable sources (EGRS) reflects advancements in decarbonizing South Africa’s power sector. While renewables are typically linked to long-term efficiency gains, short-term transitional aspects like installation energy needs, grid adjustments, and storage can momentarily increase energy intensity (Sovacool, 2009). Cereal yield (CY) signifies agricultural output, indicating how effectively land and water are utilized, which can affect national energy consumption trends, particularly in climate-sensitive farming systems (Fanadzo and Ncube, 2018).

3.2. Data Description

The study employs yearly time-series data for South Africa from 1990 to 2023, gathered from various international databases to guarantee reliability and coherence. Data regarding EI, EPRS, WP, WWI, and CY were sourced from the World Development Indicators (World Bank, 2024).

All series were transformed into natural logarithmic form (except for EPRS, which is shown as a percentage) to stabilize variance

and linearize exponential growth trends. Descriptive statistics and unit root tests (ADF and KPSS) were conducted prior to estimation to verify the mixed order of integration (I(0) and I(1)), thereby confirming the appropriateness of the ARDL method.

3.3. Variable Definitions and Expected Signs

Table 1: Variable Definitions and Expected Signs table

Variable	Description	Expected sign	Theoretical justification
EI	Energy use per unit of GDP	—	Dependent variable indicating national energy efficiency
WP	Economic output per unit of water used	(-)	Higher water efficiency is expected to reduce EI.
WWI	Water use relative to GDP	(-)	Efficient water use reduces the energy required for distribution and treatment.
EPRS	Share of electricity generation from renewable sources	Ambiguous	Transitional effects may initially raise EI before improving efficiency
CY	Cereal yield (kg per hectare)	(-)	Improved agricultural efficiency may lower aggregate EI.

3.4. Excluded Variables and Justification

Multiple possible explanatory variables were initially evaluated but dismissed due to conceptual overlap and lack of statistical significance:

- Renewable internal freshwater resources per capita (RIFWR): The restricted temporal variation and significant conceptual overlap with LWP and LWWI have redirected attention from availability to efficiency, per the WEF nexus framework
- Renewable energy consumption (REC): Omitted because of its strong correlation with EPRS, which explicitly reflects electricity-based renewables and their policy implications
- Combustible renewables and waste (CRW): Eliminated because of data inconsistencies and poor conceptual fit with clean energy goals
- Livestock production (LSP): Omitted due to strong correlation with CY ($r > 0.85$) and lack of statistical significance in initial regressions.

These exclusions improve simplicity and reduce multicollinearity, ensuring selected variables capture unique aspects of resource efficiency related to energy intensity results.

3.5. Econometric Technique

The study utilizes the autoregressive distributed lag (ARDL) method established by Pesaran et al. (2001) to assess the short-run and long-run interactions among the variables. This approach is especially appropriate for time series with small samples that

show a mix of I (0) and I (1) processes, if none are integrated of order two [I (2)].

The ARDL framework is specified as:

$$\Delta EI_t = \alpha_0 + \sum_{i=1}^p \beta_i \Delta EI_{t-i} + \sum_{i=0}^{q_1} \gamma_i \Delta LWP_{t-i} + \sum_{i=0}^{q_2} \delta_i \Delta LWWI_{t-i} + \sum_{i=0}^{q_3} \theta_i \Delta EPRS_{t-i} + \sum_{i=0}^{q_4} \phi_i \Delta CY_{t-1} + \lambda_1 EI_{t-1} + \lambda_2 LWP_{t-1} + \lambda_3 LWWI_{t-1} + \lambda_4 EPRS_{t-1} + \lambda_5 CY_{t-1} + \varepsilon_t$$

The null hypothesis, suggesting no cointegration ($H_0: \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = 0$), is examined in contrast to the alternative hypothesis indicating cointegration ($H_1: \lambda_1 \neq \lambda_2 \neq \lambda_3 \neq \lambda_4 \neq \lambda_5 \neq 0$). The calculated F-statistic is subsequently compared to the critical limits established by Pesaran et al. (2001) and Narayan (2005) for minor sample corrections.

The bounds testing method evaluates the presence of a long-term relationship between variables by examining the joint significance of lagged level coefficients. The F-statistic in this study (5.861) exceeds the upper bound value at the 1%, 5%, and 10% significance levels, suggesting long-run cointegration between EI, WP, WWI, EPRS, and CY. Having verified cointegration, the short-term dynamics are evaluated using an error correction model (ECM), which quantifies the speed of adjustment towards long-term equilibrium. The error correction term (ECT) should be negative and statistically significant, indicating a move toward equilibrium. In this model, the ECT (-0.4469, $P < 0.01$) suggests that 44.7% of any disparity in energy intensity is corrected within a single period.

Lag selection for each ARDL model was decided based on the Akaike information criterion (AIC), Schwarz criterion (SC), and Hannan–Quinn (HQ) criteria, guaranteeing optimal model fitting and simplicity. Estimations were performed with EViews 12, which allows for both automatic lag selection and the calculation of long-run multipliers.

3.6. Diagnostic and Stability Tests

To guarantee model dependability and compliance with traditional regression assumptions, numerous diagnostic tests were conducted:

- Normality: The Jarque–Bera test verified that the residuals are normally distributed ($P > 0.05$)
- Heteroskedasticity: The Breusch–Pagan–Godfrey test indicated homoscedastic errors ($P > 0.05$), confirming the constant variance assumption
- Serial correlation: The Breusch–Godfrey LM test showed no presence of autocorrelation ($P > 0.05$)
- Multicollinearity: The variance inflation factor (VIF) values were below the typical threshold of 10, suggesting that multicollinearity does not exist
- Functional specification: The Ramsey RESET test produced non-significant outcomes ($P > 0.05$), suggesting an appropriate model specification.

Moreover, the stability tests of CUSUM and CUSUMSQ confirmed that the model parameters maintained structural stability throughout the period. The residual plots stayed inside the 5% significance limits, affirming dynamic consistency and reliability.

3.7. Summary of Methodological Approach

In conclusion, the ARDL–ECM method offers a strong analytical framework for exploring resource efficiency’ short-term and long-term impacts on energy intensity in the WEF nexus. The model’s diagnostic performance, strong explanatory power ($R^2 = 0.832$), and statistically significant error correction term validate its dependability. This study offers empirical insights on South Africa’s shift towards sustainable resource management and a low-carbon economy by concentrating on variables that directly reflect water, energy, and agricultural efficiency.

4. FINDINGS AND DISCUSSION

4.1. Stationarity Test on the Original Data

This study first conducts an Augmented Dickey-Fuller (ADF) unit root test to assess the stationarity of the variables, ensuring the validity of the econometric analyses and avoiding spurious regression. Detecting the order of integration is a crucial step in identifying the most suitable modelling approach, especially given that the Autoregressive Distributed Lag (ARDL) specification requires the variables to be integrated of order zero (I(0)) or first (I(1), but not I(2) (Pesaran, Shin, & Smith, 2001). Table 2 presents the ADF unit root test results at levels and in first differences.

4.2. Interpretation of Stationarity Results

As shown in Table 2, the results suggest that the variables are integrated of mixed orders, hence justifying the use of the ARDL modelling approach.

Stationary at level [I (0)]:

Cereal Yield (CY) remains stationary at a certain level, since its ADF test statistic (-4.1119) surpasses the critical values for 1%, 5%, and 10%. This suggests that CY is mean-reverting and does not need differencing to reach stationarity. In simpler terms, disturbances to agricultural productivity are usually short-lived, as the series tends to revert to its long-term equilibrium trajectory.

Stationary at first difference [I (1)]:

On the other hand, Energy Intensity (EI), Water Productivity (WP), Water Withdrawal Intensity (WWI) and Electricity Production from Renewable Sources (EPRS) are non-stationary at levels but stationary at first differences. This is shown by the fact that ADF test statistics fail to reach the critical values at the levels but are significant at the first-difference level. This suggests that these variables follow a random walk, and shocks are not transitory unless differenced.

The presence of I (0) and I (1) variables, without any I (2), fulfils the main assumption of the ARDL bounds testing. This benefit implies the joint estimation of short-run dynamics and long-run

Table 1: Augmented dickey fuller unit root tests

Variable	P-values		t-Statistic		t-statistic and critical values			Order of integration
	Levels	First difference	Levels	First difference	1%	5%	10%	
EI	0.7806	0.0003	-1.5729	-5.7595	-4.2967	-3.5684	-3.2184	I (1)
WP	0.9840	0.0025	-0.3779	-4.8826	-4.2967	-3.5684	-3.2183	I (1)
WWI	0.7673	0.0000	-0.3037	-5.3496	-2.6443	-1.9525	-1.6121	I (1)
EPRS	0.9775	0.0005	-0.5097	-5.4959	-4.2967	-3.5684	-3.2184	I (1)
CY	0.0176	—	-4.1119	—	-4.3743	-3.6032	-3.2381	I (0)

Source: Author (s) computation using EViews

Table 2: Lag selection criterion

Lags	LogL	LR	FPE	AIC	SC	HQ
0	-2276.958	N/A	8.07e+59	152.1305	152.3641	152.2052
1	-2054.340	356.1892	1.58e+54	138.9560	140.3572	139.4042
2	-1696.827	452.8489	4.32e+44	116.7885*	119.3573*	117.6103*

*Indicates lag order selected by the criterion. LR: Sequential modified LR test statistic (each test at 5% level). FPE: Final prediction error, AIC: Akaike information criterion, SC: Schwarz information criterion. HQ: Hannan-Quinn information criterion. Source: Author(s) computation using EViews 12

Table 3: ARDL cointegration bounds test

Test statistic	Value	Significant (%)	I (0)	I (1)
F-statistic	5.861291	10	2.2	3.09
K	4	5	2.56	3.49
		2.5	2.88	3.87
		1	3.29	4.37

Source: Author(s) computation using EViews 12

equilibrium relationships, whereas in conventional cointegration methods, series of the same order of integration are assumed.

As such, the results from the unit root tests support the use of the ARDL bounds testing approach to examine the relationship between resource efficiency indicators and energy intensity in South Africa.

4.3. Lag Selection Criterion

The optimal lag length was established utilizing various information criteria, such as the likelihood ratio (LR), final prediction error (FPE), Akaike information criterion (AIC), Schwarz criterion (SC), and Hannan–Quinn criterion (HQ). According to Table 2, all selection criteria consistently point to a lag length of two (Lag = 2) as the best choice.

This result suggests that the variations in energy intensity (EI) in South Africa are primarily accounted for by its recent two observations and the delayed influences of the explanatory factors from the past two periods. Selecting a two-lag framework accounts for possible inertia and postponed changes in resource efficiency, energy generation, and agricultural yield.

This indicates that policy measures influencing renewable energy production, water usage, or farming efficiency impact energy intensity over a 2-year adjustment period. These time delays are common in studies on resource efficiency, indicating the gradual spread of technological, infrastructural, and institutional transformations throughout different sectors (Sadorsky, 2009; Chen et al., 2020).

Consequently, the lag selection outcomes verify that the model

Table 4: Estimated long run coefficients using the ARDL

Dependent variable: D (EI)				
Included observations: 26				
Variable	Coefficient	Standard error	t-Statistic	Probability
LWP	9.84258	14.2350	0.69143	0.4977
LWWI	-95.54254	27.1536	-3.51859	0.0023
EPRS	6.568075	1.37206	4.787012	0.0001
CY	0.000206	0.00119	1.720331	0.1016
C	145.4827	53.9040	2.698919	0.0142
Short-run estimates: ECM short run dynamic ARDL estimation				
D (EPRS)	5.28897	0.485901	10.8848	0.0000
CointEq(-1)*	-0.44693	0.067056	-6.66501	0.0000
Model diagnostics				
R-squared	0.832			
Adjusted R-squared	0.825			
Standard Error	0.780			
Durbin-Watson	2.436			

Source: Author(s) computation using EViews 12

configuration addresses both short-term variations and medium-term adjustment patterns, guaranteeing that the estimated ARDL model represents realistic economic behavior and dynamic stability.

4.4. ARDL Cointegration Bounds Test

The ARDL bounds testing method, as suggested by Pesaran et al. (2001), is utilized to examine the existence of a long-term equilibrium relationship between the relevant variables. In this instance, the calculated F-statistic = 5.861 significantly surpasses the upper bound critical values at all standard significance levels (e.g., 3.09 at 10%, 3.49 at 5%, 4.37 at 1%). This statistical result rejects the null hypothesis of no level relationship, thus affirming a stable long-term cointegrating relationship among energy intensity (EI) and its explanatory variables: LWP, LWWI, EPRS, and CY.

This finding indicates that although short-term fluctuations may show instability, the system typically returns to a steady long-term trajectory as time progresses. Establishing cointegration is essential for employing ARDL models, as it validates the

estimation of long-run coefficients and the short-run adjustment process via an error correction model (ECM) 1 (Pesaran et al., 2001; Narayan, 2005).

4.5. Long Run and Short Run Estimates

To assess the size and direction of effects between the indicators of resource efficiency and energy intensity, the study estimates long-run (equilibrium) and short-run (dynamic) coefficients in an Autoregressive Distributed Lag (ARDL) framework. Long-run estimates represent the equilibrium relationships in the system, while short-run estimates, obtained from the error correction model (ECM), reflect the immediate and dynamic interactions with the adjustment towards equilibrium. The results are shown in Table 5.

4.6. Long-Run and Short-Run Estimates

4.6.1. Electricity Production from Renewable Sources (EPRS)

Table 5 reports the coefficient estimates for Electricity Production from Renewable Sources (EPRS) as being positive and statistically significant in the long run (6.5681, $p < 0.01$) and short run (5.2890, $p < 0.01$), suggesting there is a strong and significant association between higher renewable energy production and greater energy intensity (EI).

While this finding may seem paradoxical - in that renewable energy is usually associated with efficiency gains - it is consistent with transitioning processes in developing and structurally dysfunctional economies. During the initial stages of renewable energy integration, system inefficiencies come to the fore. These include the higher energy input required for the production, transport, and installation of renewable technologies, as well as challenges in integrating renewables into the grid. Limited storage capacity, renewable energy variability, and pre-existing grid constraints also contribute to increased energy demand per unit of output.

This is supported by empirical analysis. Sovacool (2009) stresses that the intermittency of renewable energy requires additional capacity and grid redundancies, thereby requiring higher short-term energy inputs. Likewise, Akella et al. (2009) and Apergis and Payne (2014) show that the growth of renewable energy in developing countries could increase energy use in the short run, before long-term efficiency enhancements occur due to technological maturity and infrastructure enhancements.

4.7. Log of Water Withdrawal Intensity (LWVI)

The long-run coefficient for the Log of Water Withdrawal Intensity (LWVI) variable, as shown in Table 5, is negative and significant at 99% level (-95.5425 , $p < 0.01$), suggesting the existence of a negative long-run relationship with energy intensity. This implies that substantially improving water efficiency substantially lowers energy use, especially in water-intensive industries such as agriculture, mining, and energy generation.

Theoretically, reducing the volume of water withdrawn per unit of output decreases the energy inputs required to withdraw, treat, and supply water, thereby lowering energy intensity. This result confirms the systemic linkages in the Water–Energy–Food (WEF) nexus. This is supported by empirical studies showing

that increased water governance and irrigation efficiency lead to a simultaneous decrease in energy requirements (Ringler, Bhaduri & Lawford, 2013; Hoff, 2011). Likewise, Albrecht et al. (2018) show that water recycling and efficient irrigation technologies can reduce energy intensity in farming.

4.8. Log of Water Productivity (LWP)

The long-run coefficient for the Log of Water Productivity (LWP), as shown in Table 5, is positive but insignificant (9.8426, $p = 0.4977$), suggesting that fluctuations in water productivity do not have a systematic impact on energy intensity at the aggregate level.

This could be due to sectoral variations and measurement issues. The fact that some sectors (such as irrigated farming) may become more efficient may be counterbalanced by inefficiencies in other sectors (such as industrial or municipal water systems). The national-scale analysis may also mask regional variations. As Scott et al. (2011), and Endo et al. (2015) have shown, aggregate measures of water efficiency oftentimes mask the spatial and temporal dynamics of water-energy relations. In South Africa, Biggs et al. (2015) also note that infrastructure leakages and rebound effects prevent water efficiency gains from resulting in national energy savings.

4.9. Crop Yield (CY)

The coefficient for Cereal Yield (CY), as shown in Table 5, is positive but not significant (0.000206, $p = 0.1016$), suggesting an uncertain and limited association between farm productivity and energy intensity.

This finding results from the interplay among agricultural factors. Although increased yields can lower the pressure to expand cultivation, they increase energy requirements for mechanisation, irrigation, and fertilisers. As a result, the impact on energy intensity is unclear. This result is consistent with Burney et al. (2010) and Tilman et al. (2011), who argue that higher energy consumption is often associated with increases in productivity, even as land productivity rises. South African regional variations in farming systems also weaken the overall yield-energy nexus (van der Berg et al., 2011).

4.10. Short-Run Dynamics and Error Correction Mechanism

The short-run dynamics (see Table 5) show that the coefficient of the change in renewable energy, $D(EPRS)$, is statistically significant (5.28897, $p < 0.01$) and positive, confirming that increases in renewable energy generation have a positive effect on energy intensity in the short run. This supports the idea of inefficiency in the initial period of energy system transition.

The coefficient of the error correction term (CointEq (-1) = -0.4469 , $p < 0.01$) is negative and highly significant, thus corroborating the existence of a long-run equilibrium relationship. The absolute value of the coefficient suggests that 44.7% of the previous period's disequilibrium is adjusted in the current period, implying a relatively slow speed of adjustment to the long-run equilibrium (coefficient of 0.447).

This result is consistent with the theoretical expectations of ARDL-ECM models, in which the partial adjustment and speed of adjustment reflect structural rigidities, institutional inertia, and the gradual diffusion of technological improvements (Narayan & Smyth, 2005; Bekhet & Yusop, 2009). The significance of the coefficient on the error-correction term further affirms the previously identified cointegration relationship.

4.11. The goodness of Fit and Model Diagnostics

Several diagnostic test results, presented in Table 5, suggest that the model has strong explanatory power and good econometric properties. The R-squared (0.832) and adjusted R-squared (0.825) statistics indicate that more than 82% of the variability of the energy intensity is captured by the set of variables.

The Durbin-Watson ratio of 2.436 indicates no first-order autocorrelation, confirming the validity of the endogenous coefficient estimates. The statistical significance and the correct sign of the error correction coefficient also verify the model's dynamic stability.

In summary, these findings show that the ARDL model offers a consistent and coherent representation of the short-run and long-run dynamics and equilibrium relationships that determine energy intensity in the WEF nexus of South Africa.

5. DISCUSSION: THE NEXUS BETWEEN ENERGY INTENSITY AND THE JUST TRANSITION FRAMEWORK—EMPIRICAL INSIGHTS AND POLICY IMPLICATIONS

5.1. Transitional Dynamics of Renewable Energy and Energy Intensity

The empirical findings indicate that rises in electricity production from renewable sources (EPRS) are linked to elevated energy intensity (EI) in the short and long term. This result illustrates a frequent occurrence in initial phases of energy transitions, where the incorporation of renewables temporarily boosts total energy consumption. The production and installation of renewable infrastructure like solar panels, wind generators, and grid enhancement systems demand substantial energy resources, while intermittency and restricted storage capabilities worsen system inefficiencies (Sovacool, 2009).

In the South African setting, these results reflect existing limitations in infrastructure and technology, where the shift from a coal-centric system to renewable energy raises overall energy usage. These dynamics highlight the evolving character of clean energy routes—where efficiency improvements occur only after technological advancements, economies of scale, and system optimization have been realized.

This evidence emphasizes the necessity of balancing short-term trade-offs between decarbonization and energy efficiency within the framework of the just transition. Policy measures should concentrate on modernizing the grid, investing in storage solutions,

and helping displaced workers and impacted communities. McCall and Burgherr (2020) and Rogan and Reynolds (2021) highlight that it is essential to incorporate equity, employment, and access factors within the larger sustainability framework for a socially inclusive energy transition.

5.2. The Role of Water Efficiency in Reducing Energy Demand

According to the analysis, water withdrawal and energy intensity have a significant negative correlation, indicating that higher water-use efficiency lowers energy demand. This link is especially significant in water-heavy industries like farming, mining, and thermal electricity production—essential parts of South Africa's industrial foundation.

This result aligns with the water-energy-food (WEF) nexus literature, highlighting the interconnectedness of these systems in attaining sustainability results (Ringler et al., 2013; D'Odorico et al., 2018). In economies with limited water resources, enhancements in water management through technologies such as precision irrigation, wastewater recycling, and leak detection can significantly lower the energy needs linked to pumping, treatment, and distribution.

In South Africa, incorporating water efficiency initiatives into energy and agricultural policy frameworks can provide co-benefits, such as lower operational costs, increased resource resilience, and better advancement toward sustainable development goals (SDGs) 6 (clean water), 7 (clean energy), and 13 (climate action). These findings highlight the importance of viewing water efficiency as an environmental and energy policy tool.

5.3. Insignificant Effects of Water Productivity and Crop Yield

Even though water productivity (LWP) and cereal yield (CY) show positive coefficients, their impacts on energy intensity are not statistically significant. This indicates that, on a collective basis, enhancements in agricultural productivity and water efficiency do not consistently lead to reduced energy intensity. Multiple reasons can explain this outcome.

Productivity improvements frequently involve enhanced mechanization, irrigation, and fertilizer usage, resulting in higher energy consumption (Burney et al., 2010; Tilman et al., 2011). Secondly, the agricultural landscape of South Africa exhibits significant spatial diversity, with variations in climate, infrastructure, and technology use at regional levels that mask effects observed at the national level (van der Berg et al., 2011). Ultimately, data aggregation can obscure sector-specific trends, like advancements in efficiency for high-value crops compared to heightened energy consumption in intensive farming practices.

These results emphasize the necessity for detailed, sector-oriented evaluations to comprehend the interaction between agricultural and water productivity and energy systems. A more sophisticated empirical method might reveal structural connections across

provinces and subsectors more effectively, guiding specific actions within the larger Just Transition framework.

5.4. Short-Run Adjustments and Model Robustness

The error correction term (ECT) in the ARDL–ECM estimation is negative and significantly different from zero, indicating a long-run equilibrium relationship between the variables. Approximately 45% of deviations from long-term equilibrium are corrected in a single period (1 year), according to the value of approximately -0.45. In line with the gradual nature of institutional adaptation and structural reforms in South Africa's energy transition process, this points to a moderate but steady rate of adjustment (Narayan and Smyth, 2005).

This adaptive adjustment mechanism enhances the strength of the ARDL–ECM model in capturing both short-term variations and long-term alignment in the factors influencing energy intensity. It indicates that while policy and market shocks may briefly disturb equilibrium, the system is naturally inclined to return to balance, demonstrating enhanced coordination among resource efficiency, energy planning, and technological adaptation.

5.5. Diagnostic Tests

Thorough diagnostic assessments were performed to verify that the proposed models adhere to the classical linear regression assumptions.

The Jarque–Bera test validated the normality of residuals ($P > 0.05$), thereby meeting the assumption of Gaussian distribution (Gujarati and Porter, 2009). The Breusch–Pagan–Godfrey test showed no signs of heteroskedasticity ($P > 0.05$), suggesting homoscedastic error terms (Wooldridge, 2013). Similarly, the Breusch–Godfrey LM test indicated no serial correlation ($P > 0.05$), suggesting that residuals are independently distributed (Kutner et al., 2004).

The Breusch–Godfrey LM test similarly showed no serial correlation ($P > 0.05$), implying that the residuals are distributed independently (Kutner et al., 2004).

Variance inflation factor (VIF) analysis showed no multicollinearity, with all values staying below the 10 thresholds, suggesting low inter-variable dependence. The Ramsey RESET test validated correct model specification and structural stability, showing P-values exceeding 0.05 for each model (Kline, 2015).

6. CONCLUSION

The empirical results highlight the complex aspects of South Africa's sustainability transition. The growth of renewable energy initially raises energy intensity because of limitations in infrastructure and technology, while water efficiency becomes an essential factor in reducing energy consumption. Nonetheless, the minor impacts of agricultural productivity metrics indicate that larger structural issues and regional diversity constrain their role in enhancing energy efficiency.

These dynamics emphasize the importance of a Just Transition framework, which should harmonize economic, environmental, and social priorities. Although integrating renewable energy is crucial for reducing carbon emissions, it should be supported by policies that tackle transitional expenses, guarantee fair access, and enhance institutional capabilities.

Insights from global examples like Rwanda's Girinka and Brazil's Fome Zero programs show that effective, sustainable transitions occur when they are coordinated with inclusive social initiatives and robust governance systems. For South Africa, this entails integrating resource efficiency into a comprehensive development framework that promotes economic resilience and social fairness.

Continued investment in human capital, collaboration among institutions, and flexible policy design will be crucial to guarantee that resource efficiency improves environmental outcomes and supports long-term, fair growth and sustainable advancement.

6.1. Policy Recommendations

6.1.1. Policy recommendations

The empirical findings underscore the complex interactions between renewable energy growth, water efficiency, and energy intensity during South Africa's sustainability transition. The subsequent policy suggestions aim to enhance the coherence, inclusiveness, and effectiveness of the Just Transition framework:

6.2. Strengthening Institutional and Cross-Sectoral Coordination

Realizing sustainable energy transitions necessitates cohesive governance systems that connect the divisions among energy, water, and agricultural sectors. Forming a National Resource Efficiency Council (NREC) with representatives from the Department of Mineral Resources and Energy (DMRE), the Department of Water and Sanitation (DWS), and the Department of Agriculture, Land Reform and Rural Development (DALRRD) could enable synchronized planning and guarantee that energy and water policies support, instead of contradicting, each other.

Effective coordination is crucial for implementing the water-energy-food (WEF) nexus strategy and achieving consistency in infrastructure investments, pricing regulations, and sustainability assessments.

6.3. Promoting Technological Innovation and Energy Storage

The temporary increase in energy intensity linked to the growth of renewable energy indicates technological delays and inefficiencies in infrastructure. To address these transitional costs, policymakers should promote investment in energy storage systems, cutting-edge grid technologies, and renewable production capacities.

Increasing public–private partnerships (PPPs) in renewable energy research and encouraging localized component production might lessen reliance on imported technologies, enhancing employment and industrial diversification. Fiscal incentives—like rapid depreciation and tax credits for renewable infrastructure—would enhance private sector involvement.

6.4. Enhancing Water-Use Efficiency and Demand Management

Considering the inverse connection between water usage and energy intensity, South Africa should enhance water demand management (WDM) efforts, focusing on technological and behavioral strategies in agriculture and industry.

Policies ought to promote the use of precision irrigation, recycling of wastewater, and energy-efficient desalination technologies, particularly in regions facing severe water shortages. Implementing tiered water pricing and performance-driven rewards can encourage conservation while ensuring affordability for low-income families.

6.5. Supporting a Socially Inclusive Just Transition

The Just Transition should guarantee that the expenses of decarbonization do not worsen social inequality. Tailored initiatives must be created to retrain employees affected by decreased carbon-heavy industries and enhance access to environmentally friendly job prospects. Renewable energy initiatives owned by the community and cooperative funding models can promote local engagement, improve energy accessibility, and bolster social legitimacy during the transition process. Planning and support that consider gender, particularly for rural women in agriculture and small-scale energy production, would further enhance equity goals.

6.6. Strengthening Data Systems and Monitoring

Practical policy assessment necessitates trustworthy and frequent data. South Africa must invest in comprehensive environmental-economic data systems that merge energy consumption metrics, water extraction statistics, agricultural output, and emissions data.

Creating these databases, which are overseen by Statistics South Africa (Stats SA) and connected to the National Planning Commission (NPC), would allow policymakers to evaluate the effectiveness of policies and enhance evidence-based decision-making across various sectors.

6.7. Suggestions for Future Research

The current research offers significant empirical understanding of the factors influencing energy intensity in relation to the WEF nexus and Just Transition, yet numerous aspects deserve additional scholarly inquiry:

6.8. Disaggregated and Sectoral Analysis

Future research ought to utilize datasets at the sectoral or provincial level to reflect the diversity in energy intensity trends across agriculture, manufacturing, mining, and services. Spatial econometric models may clarify regional spillover impacts, especially in provinces with varied resource endowments and industrial compositions.

6.9. Incorporation of Institutional and Behavioral Variables

Future studies may incorporate metrics of institutional quality, governance effectiveness, and behavioral adoption of green

technologies to evaluate their intermediate impacts on resource efficiency. This would enhance comprehension of how regulatory frameworks, corruption, and civic engagement impact transition results.

6.10. Nonlinear and Asymmetric Relationships

Investigating nonlinear ARDL (NARDL) or threshold regression models could uncover asymmetric impacts of renewable energy adoption on energy intensity, differentiating between growth and decline phases of renewable progress. These methods can enhance the accuracy of policy targeting at various phases of the transition.

6.11. Dynamic Interlinkages within the WEF Nexus

Additional research should create integrated system dynamics or computable general equilibrium (CGE) models to replicate policy scenarios within the WEF nexus. Based on different climate and policy scenarios, these models might identify intertemporal feedback interactions between energy, water, and agricultural systems.

6.12. Cross-Country Comparative Studies

Comparative studies among Sub-Saharan African economies may reveal structural variations in transition paths and institutional reactions. Cross-national ARDL or panel cointegration methods might indicate if the identified South African trends apply to resource-limited and developing energy systems.

This study shows that transitional inefficiencies, institutional limitations, and structural disparities influence South Africa's journey toward sustainable energy and resource efficiency. Subsequent empirical research should expand on this groundwork by incorporating more detailed data, multifaceted indicators, and sophisticated econometric methodologies to enhance the analytical comprehension of the relationship between resource efficiency, energy transitions, and social equity.

The current investigation is essential to guide adaptive policymaking and guarantee that the country's Just Transition is environmentally sustainable and socially inclusive.

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