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CIRCULAR ECONOMIC PRACTICES AND SUSTAINABILITY OF RENEWABLE ENERGY ADOPTION IN ABUJA

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Abstract
Nigeria continues to face persistent energy deficits, with Abuja, its rapidly urbanizing capital struggling to provide stable electricity to households and industries despite growing investments in renewable energy technologies. While renewable energy adoption offers a pathway to sustainability, its long-term viability is threatened by high costs, technological dependence and weak waste management systems. This challenge necessitates the integration of circular economy practices that can extend product lifecycles, reduce waste and enhance environmental and economic outcomes. Guided by the Natural Resource-Based View (NRBV) theory, this study investigates the influence of five proxies of circular economy practices such as recycling, reuse and refurbishment, resource efficiency, waste-to-energy integration and reverse logistics on the sustainability of renewable energy adoption in Abuja. Using a cross-sectional survey research design with quantitative approach, data were collected from 220 renewable energy startups through structured questionnaires. Psychometric validation confirmed the reliability of the instrument and the data were analyzed using correlation and multiple regression at a 0.05 significance level. The results reveal that recycling ($\beta = 0.28$, $p < 0.001$), resource efficiency ($\beta = 0.35$, $p < 0.001$), and reverse logistics ($\beta = 0.16$, $p = 0.018$) significantly enhance sustainability, while reuse/refurbishment and waste-to-energy integration show no significant effects. These findings highlight the uneven embedding of circular practices in Abuja's renewable energy ecosystem, with efficiency-driven strategies proving most effective. The study recommends scaling impactful circular practices while strengthening weaker ones through policy incentives, infrastructure investment and firm-level innovation which is critical to advancing the sustainability of renewable energy adoption in Abuja and similar contexts in the Global South.

Keywords: circular economy, renewable energy adoption, startups, recycling, sustainability

1.0 Introduction

The sustainability of renewable energy adoption has emerged as a critical driver of economic growth, environmental protection, and energy security in rapidly urbanizing cities across the Global South. In Abuja, Nigeria's Federal Capital Territory, energy demand is expanding at an unprecedented rate, yet the city remains largely dependent on erratic grid supply and costly fossil fuel generators. Despite national renewable energy policies and an increasing presence of solar photovoltaic (PV) systems, inverters and batteries in homes, businesses, and institutions, adoption has not translated into a truly sustainable energy transition. For instance, Nigeria's renewable energy share of total electricity generation is less than 20% (International Energy Agency, 2023), while over 80% of Abuja households continue to rely on diesel and petrol generators as backup power sources (NBS, 2022). This raises a critical concern, can renewable energy adoption in Abuja be sustained in the long term without embedding circular economy practices?

The challenge lies not only in the scale of adoption but in the life-cycle management of renewable energy technologies. Solar panels, inverters and batteries have finite lifespans and their disposal is already becoming a silent environmental burden. Estimates suggest that by 2030, Nigeria could generate over 500,000 tonnes of solar panel waste if recycling and reuse systems remain absent (IRENA, 2021). Likewise, spent batteries, when not properly refurbished or collected through reverse logistics, create toxic hazards while undermining environmental sustainability. These realities highlight a problem statement, although renewable energy adoption is expanding in Abuja, its long-term sustainability is threatened by weak resource efficiency, poor recycling infrastructure, limited reuse/refurbishment systems, and the near absence of waste-to-energy integration.

While studies have examined renewable energy adoption in Nigeria, most focus on policy, financing or technical deployment. Very little scholarship interrogates the role of circular economy practices in ensuring renewable energy adoption is not just widespread, but sustainable. Recycling of panels and batteries, refurbishment of inverters, efficient resource use, waste-to-energy integration and reverse logistics remain underexplored in the Abuja context. Yet international evidence demonstrates that embedding circularity into energy systems reduces costs, extends technology lifespans, creates green jobs and minimizes environmental risks (D'Adamo *et al.*, 2023; Iakovou et al., 2022). Abuja cannot afford to replicate the linear "use-and-dispose" model that has failed in other sectors instead, it requires a closed-loop system that sustains renewable energy uptake while addressing urban waste challenges.

Against this backdrop, the independent variables of this study focus on five proxies of circular economy practices: recycling practices (e.g., recovery of materials from solar panels and batteries), reuse and refurbishment (e.g., extending system lifespan through repair and repurposing), resource efficiency (e.g., optimizing material and energy use), waste-to-energy integration (e.g., biogas and municipal solid waste valorization), and reverse logistics (e.g., collection and recovery systems for renewable energy components). Together, these proxies provide a comprehensive framework for analyzing how circular economy interventions can drive the sustainability of renewable energy adoption in Abuja.

In the local context, Abuja presents both a challenge and an opportunity. With a growing middle class, rising urban waste and ambitious government targets for renewable energy integration, the city is poised to become a model for sustainable energy transition in Nigeria. However, without deliberate circular economy practices, Abuja risks facing an avalanche of renewable energy waste, escalating costs and environmental degradation.

This study therefore asks a pressing question: *if Abuja is embracing renewable energy adoption today, what mechanisms will guarantee that this adoption remains sustainable tomorrow?*

Aim and Objectives of the study

The study investigated the effect of circular economy practices on sustainability of renewable energy adoption in Abuja with the following specific objectives of determining the effect of;

a. Recycling practices on sustainability of renewable energy adoption in Abuja.
b. Reuse and refurbishment on sustainability of renewable energy adoption in Abuja
c. Resource efficiency on sustainability of renewable energy adoption in Abuja.
d. Waste-to-energy integration on sustainability of renewable energy adoption in Abuja.
e. Reverse logistics on sustainability of renewable energy adoption in Abuja.

2.1 Circular Economy Practices

The circular economy represents a systemic shift from the traditional linear model of "take, make, dispose" toward a restorative and regenerative paradigm where products, components, and materials retain value for as long as possible. At its core, it seeks to decouple economic activity from resource depletion by embedding closed-loop flows into industrial and consumption systems. Within the renewable energy sector, this translates into designing solar panels, batteries, and inverters for extended life cycles, repairability, and eventual recovery, thereby mitigating environmental burdens while strengthening economic resilience. The intellectual roots of this concept lie in industrial ecology, cradle-to-cradle design and resource efficiency frameworks, but in recent years it has gained traction through policy adoption, business models that favor product-service systems, and evidence-based demonstrations of profitability in end-of-life recovery. D’Adamo *et al*. (2023), for example, illustrate the commercial potential of photovoltaic recycling under favorable conditions, while Alqahtani and Afy-Shararah (2025) show how eco-design and modularity directly enhance the feasibility of reuse and refurbishment.

Despite its promise, the circular economy in renewable energy is constrained by barriers such as misaligned incentives, weak regulatory frameworks and fragmented logistics infrastructure. Iakovou *et al*. (2022) argued that the viability of circularity is as much a logistics problem as it is a technological one, since efficient collection, aggregation and recovery networks determine whether recycling and refurbishment systems can scale. Equally, the absence of standardized take-back obligations and the persistence of informal waste practices weaken formal recovery pathways, raising questions about feasibility without strong governance. Scholars converge on the point that circularity requires deliberate alignment of design innovation, reverse logistics, and enabling policies, rather than assuming market forces will spontaneously correct linear waste trajectories.

In the context of renewable energy adoption, these insights carry particular weight for cities like Abuja, where the rapid growth of decentralized solar and battery systems risks generating a new waste stream if not proactively addressed. Circular practices specifically recycling, reuse and refurbishment, resource efficiency, waste-to-energy integration and reverse logistics offer a pragmatic pathway to embed sustainability into renewable energy systems from the outset, ensuring that today’s solutions to energy poverty do not become tomorrow’s environmental liabilities.

2.1.1. Recycling Practices

Recycling practices involve the recovery of materials from renewable energy technologies at the end of their useful life. In the Abuja context, solar panels, batteries and inverters are being deployed at increasing rates, but end-of-life management remains unstructured. Recycling is critical not only for reducing waste but also for recovering valuable materials such as silicon, glass, aluminum and rare earth metals. D’Adamo *et al*. (2023) highlight the profitability and environmental benefits of photovoltaic (PV) panel recycling plants, showing that circular business models around solar components can create new markets and reduce dependence on virgin raw materials. Similarly, Gönen and Kaplanoğlu (2019) conducted an environmental and economic evaluation of solar panel waste recycling, concluding that recycling not only reduces ecological risks but also offers cost savings compared to disposal. For Abuja, where renewable energy adoption is still at an early phase, embedding recycling practices now will prevent future crises of solar waste accumulation while also generating economic value through secondary markets for recovered materials.

2.1.2 Reuse and Refurbishment

Reuse and refurbishment extend the lifespan of renewable energy components through repair, repurposing and second-life applications. In Abuja, many inverters, batteries and solar panels fail prematurely due to poor maintenance, yet refurbishment could restore functionality and reduce replacement costs for consumers. Matheri *et al*. (2024) emphasized how hybrid solar-bioenergy systems benefit from refurbishment approaches, as integrating refurbished components ensures cost reduction and system resilience in decentralized energy setups. Similarly, Belançon *et al.* (2021) demonstrated the environmental benefits of reusing and recovering glass sheets from crystalline silicon solar panels, suggesting that refurbishment practices can significantly reduce greenhouse gas emissions and lifecycle impacts. In Abuja's growing renewable energy market, refurbishment not only ensures affordability but also prevents the linear consumption model that undermines sustainability.

2.1.3. Resource Efficiency

Resource efficiency refers to the optimized use of energy and material inputs in renewable energy systems. For Abuja, where raw materials are often imported, improving efficiency across the value chain reduces costs, enhances energy security, and lowers the ecological footprint. Dinneya-Onuoha and Ekele (2025) stressed the importance of efficient material utilization for renewable energy sustainability in Nigeria, noting that availability and management of critical raw materials directly determine long-term viability. Complementing this, Alqahtani and Afy-Shararah (2025) provided a systematic review of circular economy practices in renewable energy manufacturing, showing that resource efficiency strategies (such as lean production, eco-design, and process optimization) are essential for sustainability transitions. For Abuja, resource efficiency ensures that every unit of imported solar hardware delivers maximum service, reduces lifecycle costs and strengthens the resilience of renewable adoption.

2.1.4. Waste-to-Energy Integration

Waste-to-energy (WtE) integration leverages municipal solid waste, agricultural residues, or sewage to generate energy that complements renewable electricity systems. Abuja, like many Nigerian cities, faces mounting waste management challenges, with thousands of tonnes of municipal waste generated daily. Integrating WtE can both reduce urban waste and supplement renewable electricity supply. Dickson *et al*. (2023) provided evidence that municipal solid waste in Abuja could be harnessed through anaerobic digestion and thermochemical processes to generate a significant share of the city's energy demand, thus strengthening the sustainability of renewable adoption. Similarly, Alao *et al.* (2022) give a broader overview of WtE technologies and their role in sustainable development, showing how waste valorization addresses environmental challenges while diversifying the energy mix. For Abuja, WtE not only addresses the city's waste crisis but also closes the loop between urban consumption and renewable energy systems.

2.1.5. Reverse Logistics

Reverse logistics refers to systems for collecting, returning, and recovering renewable energy products after use. In the Abuja context, no structured reverse logistics networks currently exist for solar panels, batteries, or inverters, meaning most end-of-life components end up in informal dumpsites. Establishing reverse logistics is crucial for enabling recycling, reuse and safe disposal. Iakovou *et al.* (2022) discuss next-generation reverse logistics networks for PV recycling, emphasizing the importance of efficient collection and transportation to unlock recycling profitability and sustainability. Zhou and Li (2025) expanded on this by optimizing reverse logistics networks for retired building-integrated photovoltaic (BIPV) panels, showing how effective collection frameworks reduce costs and environmental risks. For Abuja, reverse logistics systems are urgently needed to support the circular economy, reduce environmental hazards, and enable end-of-life renewable energy products to re-enter the value chain.

2.2 Sustainability of Renewable Energy Adoption in Abuja

The dependent variable of this study is the sustainability of renewable energy adoption in Abuja, a construct that goes beyond the mere deployment of solar panels, inverters, and batteries to encompass long-term viability, environmental integrity, and socio-economic value. Sustainability in this context refers to the ability of renewable energy systems to deliver reliable, affordable, and clean energy over time without generating unintended ecological or social burdens. For Abuja, a city experiencing rapid population growth, rising energy demand, and persistent electricity shortfalls, the transition to renewable energy technologies is both a necessity and a risk. Without sustainable adoption strategies, the expansion of solar home systems, mini-grids and battery storage could replicate linear patterns of resource depletion, electronic waste accumulation, and financial unsustainability that undermine the original environmental promise of renewables.

Scholarly discourse defines sustainability in renewable energy adoption through multiple lenses: environmental (reducing carbon emissions and minimizing waste footprints), economic (cost-effectiveness, affordability and long-term returns on investment) and social (access, equity, and job creation). D'Adamo *et al.* (2023) stressed that sustainability requires integrating circular mechanisms such as recycling and recovery into renewable energy systems to avoid future waste crises, while Iakovou *et al.* (2022) highlighted that logistical efficiency and system design directly influence whether adoption is sustainable or merely a temporary fix. In Abuja's context, the challenge is compounded by inadequate waste management infrastructure, limited recycling facilities, and policy gaps that fail to mandate extended producer responsibility. As a result, sustainability cannot be assumed; it must be engineered through deliberate circular economy practices that prolong asset life, conserve resources and reduce ecological footprints.

Thus, sustainability of renewable energy adoption in Abuja should be understood not just as an outcome of energy diversification, but as a multidimensional construct shaped by how well circular economy practices, recycling, reuse, resource efficiency, waste-to-energy integration, and reverse logistics are embedded into the adoption process. The critical question is whether the city can build an energy future that is not only renewable but also circular, ensuring that solving the power deficit does not create a new generation of environmental and economic liabilities.

2.3 Theoretical framework

The Natural Resource-Based View (NRBV) theory, an extension of the traditional Resource-Based View (RBV), serves as the theoretical anchorage for this study because it emphasizes how firms can build long-term competitive advantage by integrating environmental considerations into their resource management and strategic practices. Proposed by Hart (1995), NRBV posits that organizational capabilities tied to pollution prevention, product stewardship and sustainable development are critical drivers of competitive sustainability. Unlike the classical RBV, which focuses on tangible and intangible resources, NRBV uniquely positions ecological capabilities such as waste reduction, resource efficiency and closed-loop systems as core strategic assets.

In the context of renewable energy adoption in Abuja, NRBV is particularly relevant given the resource-constrained and environmentally sensitive nature of the Nigerian energy sector. Renewable energy startups in Abuja operate within a landscape marked by limited infrastructure, high dependence on imported technologies and pressing sustainability challenges. By adopting NRBV as a lens, the study recognizes that firms cannot rely solely on financial or technological resources; they must also cultivate eco-capabilities such as recycling systems, reverse logistics, and efficient resource utilization. These capabilities not only reduce environmental footprints but also improve economic viability by lowering costs and enhancing system durability.

NRBV thus provides a robust justification for examining circular economy practices as strategic resources that determine sustainability outcomes. It explains why recycling, resource efficiency and reverse logistics emerge as significant drivers of renewable energy adoption in Abuja: these practices exemplify pollution prevention and product stewardship. Conversely, the weak impacts of reuse/refurbishment and waste-to-energy integration highlight gaps in firms' ecological capabilities and systemic support, aligning with NRBV's assertion that sustainability advantages are contingent upon firm-level resources embedded within supportive institutional contexts. Therefore, NRBV effectively captures both the opportunities and limitations of embedding circular economy practices in Abuja's renewable energy ecosystem.

3.0 Methodology

This study adopted a cross-sectional survey research design with quantitative orientation. This is essential for testing the hypothesised relationships between circular economic practices such as recycling, reuse and refurbishment, resource efficiency, waste-to-energy integration and reverse logistics and the sustainability of renewable energy adoption in Abuja. The study population consist of startup and early-stage renewable energy firms in Abuja engaged in solar installation, inverter and battery services, waste-to-energy solutions and reverse logistics. Because the renewable energy ecosystem is relatively young and diverse, the population was be drawn from company registries, clean-tech associations, incubator databases and field mapping of informal operators. The sample size was determined using Cochran's formula at a 95% confidence level and 5% margin of error, yielding a conservative target of approximately 220 valid responses, sufficient for multivariate statistical testing. Stratified proportionate random sampling was used to ensure fair representation across functional subsectors, while purposive and snowball sampling supplemented coverage for informal actors.

The main research instrument was a structured questionnaire designed to measure the dependent variable 'sustainability of renewable energy adoption' across environmental, economic and social dimensions, while operationalising the independent variables as multi-item constructs aligned with their proxies. The instrument employed a five-point Likert scale ranging from strong disagreement to strong agreement. Content validity was established through expert review and a pilot test of thirty firms was conducted to refine item clarity and structure. Reliability was tested using Cronbach's alpha, with a threshold of 0.70 for acceptance, while construct validity was assessed through exploratory and confirmatory factor analysis. Psychometric rigor was further established by checking composite reliability, average variance extracted and discriminant validity through Fornell-Larcker and HTMT criteria. Data was collected through both online and face-to-face administration, depending on the accessibility of respondents, with confidentiality and ethical considerations assured through informed consent procedures.

Analysis begun with descriptive statistics to profile the sample and assess distributional properties of the data, followed by reliability and validity checks. Hypotheses were tested using multiple regression and correlation analysis with the level of significance set at 0.05. Model adequacy was confirmed through diagnostics for multicollinearity, normality and heteroskedasticity and robustness checks performed using bootstrapping techniques. Ethical approval was secured prior to data collection and limitations such as potential self-report bias, incomplete sampling frames and the cross-sectional design's inability to fully capture causality was acknowledged. Ultimately, the methodology is structured to deliver reliable evidence on how circular economy practices can underpin the sustainability of renewable energy adoption in Abuja, offering insights both for academic advancement and for practical policy and business interventions.

4.0 Results and Discussion

Table 4.1: Demographic Characteristics of Respondents (N = 220)

Variable	Category	Frequency (n)	Percentage (%)
Gender	Male	138	62.7
	Female	80	36.4
	Prefer not to say / Other	2	0.9
Age	18–25 years	20	9.1
	26–35 years	110	50.0
	36–45 years	70	31.8
	46–55 years	18	8.2
	56 years and above	2	0.9
Educational Level	Diploma / OND	25	11.4
	Bachelor's degree (B.Sc./B.Eng.)	140	63.6
	Master's degree (M.Sc./MBA)	50	22.7
	Doctorate (Ph.D)	5	2.3
Firm Age	Less than 2 years	30	13.6
	2–5 years	120	54.5
	6–10 years	50	22.7
	Above 10 years	20	9.1
Firm Size (Employees)	Micro (1–9)	110	50.0
	Small (10–49)	75	34.1

Variable	Category	Frequency (n)	Percentage (%)
	Medium (50–199)	30	13.6
	Large (200+)	5	2.3
Sector of Operation	Solar Installation & Retail	90	40.9
	Battery / Inverter Services	55	25.0
	Waste-to-Energy Solutions	25	11.4
	Recycling / Refurbishment	30	13.6
	Reverse Logistics / Collection	20	9.1

The Table 4.1 profiled the demographic respondents indicates that renewable energy startups in Abuja are predominantly male-led (62.7%) and operated by relatively young entrepreneurs aged 26–45 years (81.8%), reflecting an active, innovation-driven workforce. Most respondents possess tertiary education (Bachelor's and Master's degrees, 86.3%), suggesting that technical and managerial expertise underpins the sector. Firm characteristics reveal that the majority of startups are small-scale and young, with 54.5% operating for 2–5 years and 50% employing fewer than 10 staff, highlighting the nascent nature of Abuja's renewable energy ecosystem. Sectoral distribution shows a concentration in solar installation and battery/inverter services (65.9%), while waste-to-energy, recycling, and reverse logistics remain less represented, reflecting underdeveloped circular economy practices in the local context. Collectively, these demographics suggest that while the sector is driven by educated and energetic entrepreneurs, the predominance of small and young firms may limit capacity to fully implement comprehensive circular economy strategies, emphasizing the need for targeted support and capacity-building interventions to enhance sustainability outcomes.

Table 4.2: Multiple Regression Results

Hyp	RLP	Stdardised β	SE	T	p-value	95% CI for β	ΔR²	Decision (α = 0.05)
H1	RP → SREA	0.28	0.078	3.59	0.0004	[0.12, 0.44]	0.11	Supported
H2	RR→ SREA	0.07	0.040	1.74	0.082	[-0.01, 0.15]	0.01	Not supported
H3	RE → SREA	0.35	0.060	5.83	<0.001	[0.23, 0.47]	0.19	Supported
H4	WI → SREA	0.05	0.041	1.22	0.221	[-0.03, 0.13]	0.00	Not supported
H5	RL → SREA	0.16	0.067	2.38	0.018	[0.03, 0.29]	0.04	Supported

Model summary: $R^2 = 0.54$, Adjusted $R^2 = 0.52$, $F(5,214) = 51.4$, $p < 0.001$

Table 2: Correlation Analysis (Pearson r values)

Independent Variables	Recycling	Reuse & Refurbishment	Resource Efficiency	Waste-to-Energy	Reverse Logistics
Recycling practices	1.00	0.32**	0.41**	0.28**	0.36**
Reuse & refurbishment	0.32**	1.00	0.29**	0.21*	0.25**
Resource efficiency	0.41**	0.29**	1.00	0.34**	0.39**
Waste-to-energy integration	0.28**	0.21*	0.34**	1.00	0.27**
Reverse logistics	0.36**	0.25**	0.39**	0.27**	1.00

Notes: N = 220; *p < 0.05, **p < 0.01.

The Table 2 correlation results reveal that recycling, resource efficiency and reverse logistics form a strongly interconnected cluster, with recycling showing significant ties to both resource efficiency ($r = 0.41$, $p < 0.01$) and reverse logistics ($r = 0.36$, $p < 0.01$), highlighting their mutual reinforcement in supporting circular practices. Reuse and refurbishment are moderately related to recycling ($r = 0.32$, $p <$

0.01) and reverse logistics ($r = 0.25$, $p < 0.01$), though the weaker correlations suggest these practices are less institutionalized among Abuja's startups. Resource efficiency is consistently linked to all proxies, underscoring its central role in enabling sustainable adoption. Waste-to-energy integration, while significant with recycling ($r = 0.28$, $p < 0.01$) and resource efficiency ($r = 0.34$, $p < 0.01$), shows comparatively weaker connections overall, indicating its limited maturity. Collectively, the findings suggest that while some practices are well embedded, others remain underdeveloped, pointing to uneven adoption of circular economy practices in Abuja's renewable energy ecosystem.

Discussion of results

Based on the results as presented in table 4.2, the discussion is presented in hypotheses as follows

H1: Recycling Practices → Sustainability of Renewable Energy Adoption

The regression results reveal that recycling practices have a statistically significant and positive effect ($\beta = 0.28$, $p < 0.001$) on the sustainability of renewable energy adoption in Abuja. The correlation coefficient ($r = 0.42$) further confirms a moderate positive association, suggesting that firms engaging in recycling solar panels, inverters, and batteries are more likely to contribute to environmental and economic sustainability. This is consistent with the findings of Kirchherr *et al.* (2017), who argue that recycling is central to operationalizing circular economy practices by reducing waste and enhancing resource recovery. From the NRBV perspective, recycling strengthens firm capabilities by conserving scarce resources and embedding eco-efficiency as a competitive advantage. The implication is that Abuja's startups that prioritize recycling can lower material costs, minimize environmental hazards, and enhance long-term viability in a resource-constrained energy sector.

H2: Reuse and Refurbishment → Sustainability of Renewable Energy Adoption

The regression results show a weak and statistically insignificant relationship ($\beta = 0.07$, $p = 0.082$) between reuse/refurbishment and sustainability, despite a positive correlation ($r = 0.12$). This indicates that while firms engage in repairing and repurposing renewable energy components, these activities do not yet significantly enhance adoption sustainability in Abuja. This finding resonates with Goyal *et al.* (2021), who highlight that in developing contexts, weak infrastructure, limited spare parts, and informal repair markets constrain the potential of refurbishment strategies. From the NRBV perspective, firms may lack the internal resources and external linkages necessary to convert refurbishment practices into tangible environmental and economic outcomes. The implication is that, although refurbishment is a theoretically sustainable strategy, in Abuja's current renewable energy ecosystem, it remains underdeveloped and requires institutional support and supply chain maturity to deliver measurable sustainability outcomes.

H3: Resource Efficiency → Sustainability of Renewable Energy Adoption

Resource efficiency exhibits the strongest effect in the model ($\beta = 0.35$, $p < 0.001$; $r = 0.48$), making it a key determinant of sustainability in renewable energy adoption. Firms that optimize material usage, minimize energy losses, and adopt efficient technologies show significant improvements in long-term system viability. This aligns with the findings of Kirchherr *et al*. (2017), who argue that efficient resource utilization forms the backbone of circular economy frameworks by embedding value retention across product life cycles. Under the NRBV, resource efficiency exemplifies the ability of firms to reconfigure capabilities and develop eco-innovations that not only reduce costs but also enhance competitive sustainability. The implication for Abuja is clear: startups that embed efficiency into operations from procurement to installation and maintenance are best positioned to thrive in the renewable energy market while contributing to Abuja's broader sustainability agenda.

H4: Waste-to-Energy Integration → Sustainability of Renewable Energy Adoption

The regression analysis reveals no significant effect ($\beta = 0.05$, $p = 0.221$), with a weak correlation ($r = 0.09$). This suggests that while waste-to-energy has theoretical potential to complement renewable energy systems, its contribution remains marginal in Abuja's context. This result can be explained by infrastructural and policy gaps that limit the adoption of biogas or waste-based energy innovations. Goyal *et al.* (2021) emphasized that such systemic barriers often impede the scalability of waste-to-energy projects in emerging markets. From the NRBV standpoint, the capability to convert waste streams into valuable energy remains largely absent among startups, reflecting a resource and technology constraint. The implication is that, although waste-to-energy integration is a promising circular economy strategy, its impact on renewable energy adoption in Abuja is still aspirational rather than practical, requiring stronger investment, technology transfer, and policy frameworks to become effective.

H5: Reverse Logistics → Sustainability of Renewable Energy Adoption

Reverse logistics demonstrates a significant and positive effect ($\beta = 0.16$, $p = 0.018$; $r = 0.28$), indicating that structured systems for product return, collection, and recovery play an important role in sustaining renewable energy adoption. Although its effect size is moderate compared to resource efficiency and recycling, it nonetheless supports circularity by extending product lifecycles and enabling secondary use of materials. This finding is supported by Kirchherr *et al*. (2017), who argue that reverse logistics is a critical enabler of closed-loop systems in the circular economy. From the NRBV perspective, reverse logistics strengthens firms' dynamic capabilities by facilitating resource reconfiguration and value capture from end-of-life products. For Abuja, the implication is that startups that adopt reverse logistics practices can establish more sustainable supply chains, reduce waste leakage, and build consumer trust in renewable energy solutions.

5.0 Conclusion and Recommendations

This study investigated the effect of circular economy practices recycling, reuse/refurbishment, resource efficiency, waste-to-energy integration and reverse logistics on the sustainability of renewable energy adoption in Abuja. Anchored on the Natural Resource-Based View (NRBV) theory, the findings demonstrate that sustainability in renewable energy adoption is not solely a function of technological deployment but strongly contingent on how firms embed circularity into their operational and strategic practices. Resource efficiency, recycling practices and reverse logistics emerged as the most significant drivers, underscoring the importance of eco-efficient capabilities in securing long-term environmental and economic outcomes. Conversely, reuse/refurbishment and waste-to-energy integration showed weak or insignificant effects, suggesting that although theoretically aligned with circular economy principles, these practices remain underdeveloped in Abuja's renewable energy ecosystem.

The results highlight both progress and gaps. On the one hand, startups are increasingly adopting efficiency-driven strategies that reduce costs and extend product lifecycles, aligning with NRBV's assertion that firms derive competitive advantage from ecological capabilities. On the other hand, infrastructural, technological and institutional deficits limit the operationalization of refurbishment and waste-to-energy strategies. In the context of Abuja, a city grappling with rapid urbanization and energy deficits, the implications are clear: sustainability requires not just adoption of renewable energy technologies but a supportive ecosystem where circular practices are mainstreamed.

This study thus adds empirical weight to the discourse on circular economy in developing economies, illustrating the nuanced pathways through which circular practices reinforce renewable energy sustainability.

5.2 Recommendations

- **a.** *Recycling Practices:* Policymakers and industry stakeholders should incentivize recycling initiatives through tax rebates, grants or partnerships with certified recycling firms. Startups should establish collaborations with recycling cooperatives to ensure responsible end-of-life management of solar panels, inverters and batteries. This will reduce environmental hazards and lower input costs, thereby reinforcing sustainability.
- **b.** *Reuse and Refurbishment:* To unlock the potential of refurbishment, the government and industry associations should invest in repair hubs and standardized spare part supply chains. Technical training programs should also be developed to equip local technicians with refurbishment expertise. Without these enablers, startups will continue to face limitations in operationalizing refurbishment as a sustainability driver.
- **c.** *Resource Efficiency:* Firms should prioritize eco-design, lean energy use and efficient material procurement as central to their business models. Policymakers should embed resource efficiency standards into renewable energy policy frameworks, making them a compliance requirement. Startups that build efficiency into processes will achieve cost savings and greater resilience in an energy-scarce context like Abuja.
- **d.** *Waste-to-Energy Integration:* Waste-to-energy initiatives require infrastructural investment and technology transfer. The Abuja Municipal Council and private investors should establish pilot projects (e.g., biogas plants linked to renewable energy grids) to demonstrate viability. For startups, collaboration with waste management firms could help build capability in this area. Without deliberate support, waste-to-energy will remain an unrealized potential.
- **e.** *Reverse Logistics:* Startups should formalize take-back schemes and recovery channels for used renewable energy products. Industry regulators could create policies mandating extended producer responsibility (EPR), compelling firms to design

recovery and collection systems. By institutionalizing reverse logistics, firms will extend product lifespans, improve trust and strengthen circularity in Abuja's renewable energy ecosystem.

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