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Closing the Loop: A Comprehensive Circular Economy Roadmap for Nigeria and Ghana's Petrochemical Sector

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Abstract

The West African petrochemical industry is a primary driver of regional economic growth but contributes disproportionately to environmental degradation through gas flaring, fugitive emissions, and plastic pollution. This study develops a Circular Economy (CE) roadmap for Nigeria and Ghana's petrochemical sector, the two economies for which sufficiently granular flaring, refining, and waste data are available in the reviewed literature. Evidence was assembled through a systematic literature review (SLR) of 59 peer-reviewed and institutional sources published between 2013 and 2025, combined with a structured comparative policy analysis benchmarking Nigerian and Ghanaian regulatory instruments against the European Union's Circular Economy Action Plan (CEAP). Waste and emission hotspots were prioritized using a multi-criteria synthesis of reported loss volume, monetary value, health/environmental impact, and policy salience (Section 2). Results show that current regulatory frameworks exhibit "isomorphic mimicry," where policies exist in form but lack enforcement mechanisms compared to global standards. A structured barrier analysis further identifies fossil fuel subsidies as a major market distortion hindering the competitiveness of secondary raw materials. Based on a back-casting framework, we propose a three-phase intervention strategy: short-term gas-to-power utilization, medium-term industrial symbiosis, and long-term chemical recycling. A bottom-up, order-of-magnitude calculation (Section 3.4) indicates that currently quantifiable waste streams alone, flared gas, recoverable flaring fines, and divertible plastic waste represent on the order of US$ 2 - 3 billion in annual secondary-market value, with additional but currently unquantified value in sludge and spent-catalyst recovery. We conclude that transitioning to circularity offers Nigeria and Ghana a dual dividend: mitigating climate risk while unlocking substantial secondary-material value, conditional on closing the financing, infrastructure, and governance gaps identified below.

Keywords

Circular Economy, West Africa, Nigeria, Ghana, Petrochemical Industry, Gas Flaring, Industrial Symbiosis, Plastic Pollution, Waste Mapping

1. Introduction

The oil and gas value chain in West Africa, led notably by Nigeria and Ghana, is the geopolitical and economic spine of the sub-region. In Nigeria alone, the petroleum sector accounts for approximately 90% of total export earnings and over 50% of government revenue, underscoring its critical role in national stability [1]. Similarly, since the discovery of the Jubilee Field, Ghana's hydrocarbon sector has grown to contribute significantly to national GDP, reshaping the country's industrial landscape [2]. This economic reliance comes at a steep environmental cost. The sector operates predominantly on a Linear Economic Model ("Take-Make-Dispose"), where fossil resources are extracted, processed into fuels and petrochemicals, and ultimately discarded as unmanaged waste or atmospheric pollutants. This linearity creates a "double burden": upstream, the region remains a global hotspot for gas flaring, with Nigeria ranking among the top seven flaring countries globally and releasing millions of tonnes of CO_2-equivalent annually [3]; downstream, petrochemical byproducts (specifically single-use plastics) have outpaced municipal waste management capacities, leading to severe marine pollution in the Gulf of Guinea [4].

A Circular Economy (CE) offers a restorative alternative to this extractive status quo. Defined by the Ellen MacArthur Foundation as an industrial system that is restorative or regenerative by intention and design, CE aims to decouple economic activity from the consumption of finite resources [5]. Unlike the linear model, which treats waste as an endpoint, CE principles—designing out waste, keeping products in use, and regenerating natural systems—treat waste as a "misallocated resource." While CE literature has proliferated globally, most studies focus on European or Asian contexts (e.g., China's Circular Economy Promotion Law). Research tailoring CE roadmaps to the West African context, characterized by infrastructure deficits, cross-border regulatory fragmentation, and a dominant informal waste sector, remains scarce [6]. This paper aims to bridge that gap.

1.1. Geographic Scope

This study is anchored empirically in Nigeria and Ghana. These two countries were selected because they are the only ECOWAS member states for which the SLR (Section 2.1) returned sufficient quantitative, source-attributable data on flaring volumes, refinery losses, plastic waste generation, and regulatory instruments to support the hotspot mapping and policy benchmarking conducted here. The title refers to "West Africa" because Nigeria and Ghana together account for the large majority of the sub-region's petrochemical output and gas flaring volume, and because several of the structural barriers identified—the Bamako Convention's import restrictions, the ECOWAS Common External Tariff, and the absence of harmonized End-of-Waste criteria—apply at the regional (ECOWAS) rather than national level. Conclusions specific to Nigerian and Ghanaian institutions (e.g., the Petroleum Industry Act, Act 917) should not be generalized to other ECOWAS states without independent verification of their own regulatory and data landscapes; this constraint is revisited in Section 7.

1.2. Aim and Contribution

By mapping waste hotspots and benchmarking regional policy against global standards, we propose a pragmatic, evidence-based roadmap to transition Nigeria and Ghana's petrochemical sector from linear extraction to circular regeneration. The contribution of this paper is threefold: i) a value-chain mapping of waste and emission hotspots prioritized against explicit criteria (Section 2.3); ii) a structured comparative benchmark of national regulation against the EU CEAP; and iii) a phased, three-horizon implementation roadmap grounded in existing regional pilot projects and financing instruments.

2. Methods

This study uses a mixed-method design, combining a systematic literature review (SLR) with a structured comparative policy analysis. Both procedures are described below, together with the explicit criteria used to prioritize hotspots and barriers, and the approach used to derive the secondary-market estimate reported in Section 3.4.

2.1. Systematic Literature Review Protocol

Sources were retrieved from four databases: Scopus, Web of Science, ScienceDirect, and Google Scholar, the last used to capture institutional and grey literature (World Bank, IMF, AfDB, NEITI, PIAC, and national regulator reports) not indexed in the first three. Search strings combined three term clusters with Boolean operators: i) "circular economy" OR "circularity" OR "industrial symbiosis" OR "resource recovery"; ii) "petrochemical*" OR "oil and gas" OR "petroleum" OR "refinery" OR "gas flaring" OR "plastic waste"; iii) "West Africa" OR "Nigeria" OR "Ghana" OR "ECOWAS." Records were restricted to English-language publications dated between January 2013 (the year of the Ellen MacArthur Foundation's foundational CE report [5]) and March 2025.

Screening was conducted in two stages. Title/abstract screening included records that addressed waste, emissions, or circularity within the petrochemical or oil and gas value chain and that either concerned Nigeria or Ghana directly or provided a policy or technical benchmark applicable to them. Full-text screening then excluded records lacking primary quantitative data, duplicate reports, and superseded editions of recurring institutional publications (e.g., earlier Global Gas Flaring Tracker editions superseded by the 2023 edition). Grey-literature and institutional sources were retained only where they supplied the sole available quantitative figure for a given claim (e.g., NEITI audit data on crude theft volumes) and were cross-checked against at least one independent source where a second source existed. This process yielded 59 sources meeting full eligibility, which form the reference list underlying this review; the search, screening, and eligibility parameters above are reported so that the review can be reproduced or updated.

2.2. Comparative Policy Analysis Procedure

The comparative policy analysis benchmarks Nigerian and Ghanaian regulatory instruments against the European Union's Circular Economy Action Plan (CEAP), selected as the reference framework because it is the most comprehensively documented and most frequently cited circular economy policy architecture among the sources retained in the SLR. Four comparison criteria were applied, derived iteratively from themes recurring across the reviewed literature: i) core regulatory philosophy (end-of-pipe remediation versus life-cycle control); ii) producer responsibility mechanisms; iii) gas and emissions management instruments; and iv) financial incentive structures. For each criterion, the applicable Nigerian or Ghanaian legal instrument (e.g., the Petroleum Industry Act, the Associated Gas Re-injection Act, Act 917) was documented and its implementation status characterized using enforcement, funding, and compliance evidence drawn from institutional audit reports (NEITI, PIAC) and the secondary literature identified in Section 2.1. This is a structured qualitative comparison, summarized in **Table 1**, rather than a statistical or econometric analysis.

Table 1. A comparative analysis of Nigerian/Ghanaian regulatory frameworks against European Union best practice.

Feature	EU Circular Economy Action Plan (Global Standard)	Nigeria/Ghana Regulatory Landscape (Current State)
Core Philosophy	Life-cycle thinking; "Design for Recyclability."	Waste management and remediation (end-of-pipe).
Producer Responsibility	Mandatory Extended Producer Responsibility (EPR) for packaging.	Emerging voluntary EPR schemes (e.g., Nigeria), but with weak enforcement [3].
Gas Management	Strict methane regulations and carbon pricing.	Anti-flaring laws exist (e.g., Nigeria's PIA), but penalties are often less expensive than compliance.
Incentives	Substantial green financing and tax breaks for circular technology.	Prevalent fossil fuel subsidies distort the market against recycling.

2.3. Hotspot and Barrier Prioritization Criteria

Waste and emission "hotspots" were identified from the SLR and then prioritized using a multi-criteria qualitative synthesis of four dimensions reported across the retained sources: i) volume of material or energy loss; ii) quantified economic loss, in USD, where reported; iii) documented health or environmental impact; and iv) policy salience, *i.e.*, whether the issue is already the subject of an active but underperforming regulatory instrument. A hotspot was elevated to short-term (Phase 1) priority in the roadmap (Section 4) where evidence converged across all four criteria; gas flaring is the clearest example, combining a large and monetizable volume, a multi-hundred-million-to-billion-dollar valuation, an established health-impact literature, and an existing but historically unenforced legal instrument (the Associated Gas Re-injection Act and, subsequently, the Petroleum Industry Act). Issues supported by only one or two criteria, for example, spent catalyst stockpiling, which is well-documented on volume and hazard classification but lacks published fiscal valuation, were treated as medium or long-term priorities pending better data. This is a structured qualitative ranking, not a statistical weighting procedure, and is reported as such; the evidence supporting each criterion is cited at first mention in Section 3.1.

Barriers (Section 3.3) were classified into three categories (financial, technical/infrastructural, and governance) based on the dominant obstacle type reported across the sources addressing each intervention. A barrier is presented as primary or structural where it is corroborated by more than one independent source (e.g., fossil fuel subsidies undermining recycled-material price competitiveness, corroborated in [7]-[9]); barriers supported by a single source or case example are presented as illustrative rather than systemic, and are flagged as such in the text.

2.4. Secondary-Market Estimation Approach

The reference in the abstract to a multibillion-dollar secondary market is a bottom-up, order-of-magnitude estimate rather than a formal market-sizing study, and it is presented as such throughout the paper. It aggregates the monetizable value of waste streams already quantified in Section 3.1 using the most recent institutional figures available: i) associated gas currently flared rather than monetized in Nigeria and Ghana; ii) flaring penalties assessed but not collected in Nigeria; and iii) the incremental market value of plastic waste divertible from landfill/leakage to mechanical or chemical recycling in both countries. Each component, its underlying assumption, and its source are reported individually in **Table 2**, together with two waste streams (refinery sludge and spent catalysts) for which the reviewed literature reports composition and hazard data but not the tonnage or price data needed to produce a defensible valuation; these are noted as data gaps rather than assigned an invented figure. Because the quantified components draw on different base years and exchange-rate assumptions, the aggregate is reported as an indicative range, and its limitations are revisited in Section 7.2.

Table 2. Bottom-up, order-of-magnitude estimate of currently quantifiable annual secondary-material value (Nigeria and Ghana combined).

Waste stream	Basis/assumption	Estimated annual value (USD)	Source
Flared associated gas (monetization potential)	Nigeria $1.05B (2024) + Ghana $0.17 B (2024) flared-gas value; consistent with the $1.2 B cross-country monetization estimate.	~$1.2 billion	[11], [13], [17]
Uncollected flaring penalties (Nigeria, recoverable arrears)	Fines assessed under the PIA but not collected in 2024 due to weak enforcement.	~$0.60 billion	[12]
Plastic waste divertible to recycling (Nigeria + Ghana)	Illustrative uplift from current recycling rates (Nigeria < 12%; Ghana partial) applied to a combined ~3.3 Mt/yr of generated plastic waste, at typical recycled-resin value premia; presented as an indicative range, not a market forecast.	~$0.3 - 0.6 billion (indicative)	[9], [23], [24]
Refinery sludge—recoverable hydrocarbon value	Composition (55% water/30% hydrocarbon/15% solids) is reported [20], but regional tonnage and price data needed for valuation were not identified in the reviewed literature.	Not currently quantifiable—data gap	[20]
Spent FCC catalysts—recoverable metals value	Hazard classification and metal content were reported [26], but regional stockpile tonnage was not identified in the reviewed literature.	Not currently quantifiable—data gap	[26]
Indicative total (quantifiable streams only)	Sum of the three quantified rows above.	~$2.1 - 2.4 billion/year	—

3. Results

This section reports the waste and emission hotspots identified across the upstream, midstream, and downstream value chain (3.1); the outcome of the comparative policy benchmark (3.2); the barrier analysis (3.3); and the secondary-market estimate derived using the approach set out in Section 2.4 (3.4).

3.1. Waste and Emission Hotspots across the Value Chain

3.1.1. Upstream: The Gas Flaring Challenge

The most significant circularity gap in the upstream sector is the systemic wastage of Associated Petroleum Gas (APG). Despite repeated regulatory deadlines to end the practice (e.g., Nigeria's "Zero Routine Flaring by 2030"), Nigeria and Ghana remain global hotspots for gas flaring. This represents a "triple loss": a waste of valuable economic resources, a driver of climate change, and a direct threat to local public health [10].

1) Economic Leakage and Resource Waste

Nigeria: In 2024 alone, Nigeria flared associated gas valued at approximately

$1.05 billion. This volume of gas had the potential to generate 30.1 thousand Gigawatt-hours (GWh) of electricity, enough to significantly bridge the nation's power deficit [11]. Despite the Petroleum Industry Act (PIA) imposing penalties, an estimated $602 million in flaring fines remained uncollected in 2024 due to weak enforcement [12].

Ghana: The situation mirrors its neighbor. In 2024, Ghana flared 28.5 billion cubic feet of natural gas, a loss valued at $170 million [13]. This wastage occurs primarily because processing infrastructure (such as the Atuabo Gas Plant) lacks the capacity to handle peak production volumes from the Jubilee and TEN fields.

2) Environmental and Health Externalities

Flaring releases a cocktail of hazardous pollutants, including sulfur dioxide (SO2), nitrogen oxides (NOx), and particulate matter (soot). Research in the Niger Delta has established a direct correlation between flaring proximity and hypertension, with residents in flaring communities showing significantly higher blood pressure profiles than control groups [14]. A World Bank study found that children under five living near flare sites suffer from higher rates of wasting (low weight-for-height) and respiratory illnesses compared to those further away, due to inhalation of incomplete combustion byproducts [15]. The release of acidic oxides has altered the pH of rainwater in the Delta to as low as 4.34 (compared to a normal ~5.6), acidifying soil and reducing crop yields; this degradation threatens endemic species such as the West African manatee (Trichechus senegalensis) and the pygmy hippopotamus, whose habitats are eroded by pollution-induced vegetation loss [16].

3) Circular Opportunity: Gas-to-X

From a circular economy perspective, APG is not waste but a "misallocated resource," comprising methane-rich associated gas (>90% methane), produced water, and hydrocarbon sludge. Converting APG via Gas-to-Power (local micro-grids) or Gas-to-Liquids (GTL) technologies could monetize an estimated $1.2 billion lost annually across Nigeria and Ghana while reducing the carbon intensity of West African crude by up to 40% [17].

3.1.2. Midstream: Transportation and Processing Losses

Midstream operations suffer from an infrastructure deficit that results in the physical loss of hydrocarbons and high energy intensity during processing. Three critical leakage points were identified: pipeline vandalism, refinery inefficiency, and fugitive methane emissions.

1) Physical Losses: Theft and Vandalism

The Nigerian Extractive Industries Transparency Initiative (NEITI) reports that in the 2022/2023 fiscal period alone, Nigeria lost 13.5 million barrels of crude oil to theft and sabotage, valued at approximately $3.3 billion [18]. While the Nigerian Upstream Petroleum Regulatory Commission (NUPRC) noted a reduction in daily losses to 9,600 barrels per day (bpd) in 2025, down from 102,000 bpd in 2021, due to improved surveillance, the cumulative economic hemorrhage remains severe. Ghana offers a contrasting case: the state-owned Bulk Oil Storage and Transportation Company (BOST) reversed a trend of operational losses (GH¢292 m in 2020) to post a GH¢398 million profit in 2024, driven by automated flow meters and leak detection systems that minimized product transit losses [19].

2) Processing Inefficiencies: The "Sludge" Problem

West Africa's state-owned refineries (e.g., Tema Oil Refinery in Ghana, Port Harcourt Refinery in Nigeria) are characterized by low capacity utilization and high waste generation due to obsolete technology. A major by-product is "oily sludge," a hazardous emulsion generated during tank cleaning and wastewater treatment; analysis of sludge from West African facilities reveals it typically comprises 55% water, 30% hydrocarbons, and 15% solids (including heavy metals such as vanadium and nickel) [20]. This is currently treated largely as waste for incineration or landfilling, representing a loss of recoverable energy. For every barrel of crude oil processed in older regional refineries, approximately 1.6 barrels of wastewater are generated, often containing high loads of phenols and suspended solids, requiring energy-intensive treatment before discharge [21].

3) Fugitive Emissions: The Invisible Waste

Beyond visible spills, the midstream sector is a major source of unintentional natural gas leaks from valves, flanges, and seals. Satellite data indicate that oil and gas operations account for ~48% of anthropogenic methane emissions in Africa [22]; in Nigeria, venting from aging midstream infrastructure contributes significantly to the region's carbon footprint. Unlike flaring, which burns gas to CO_2, venting releases pure methane, which has a Global Warming Potential (GWP) 84 times higher than CO_2 over a 20-year period.

4) Circular Opportunity: Recovery and Retrofit

Sludge-to-fuel technologies (solvent extraction or centrifuge) could recover up to 90% of the oil currently lost in sludge, returning it to the refinery feedstock pool. Retrofitting storage tanks with Vapor Recovery Units (VRUs) can capture fugitive methane and volatile organic compounds (VOCs) for use as fuel gas within the refinery, creating a closed-loop energy system.

3.1.3. Downstream: The Petrochemical Glut and Plastic Crisis

The downstream sector is characterized by a "production-management mismatch": domestic petrochemical capacity is expanding (e.g., the Indorama Eleme expansion and the Dangote Refinery's polypropylene unit), while municipal waste management infrastructure remains nascent. This asymmetry has created a pervasive pollution crisis driven by single-use plastics (SUPs) and hazardous industrial by-products.

1) The "Sachet Economy" and Post-Consumer Waste

Nigeria generates approximately 2.5 million tonnes of plastic waste annually, of which less than 12% is recycled; the remainder ends up in landfills, uncontrolled dumpsites, or flows into the Atlantic Ocean via the Niger Delta [23]. Ghana generates 0.84 million tonnes annually, with a plastic leakage rate of approximately 73,000 tonnes into marine environments per year [24]. Unlike the Global North, where PET bottles dominate, West Africa struggles specifically with Low-Density

Polyethylene (LDPE) from "pure water" sachets, which clog municipal drainage systems and exacerbate annual flooding in cities like Lagos and Accra. This plastic glut degrades marine biodiversity and creates microplastic contamination in the local food web, posing a direct threat to food security [25].

2) Industrial Hazardous Waste

The downstream sector also generates significant invisible hazardous waste during refining and polymerization. Spent zeolite-based catalysts from Fluid Catalytic Cracking (FCC) units are classified as hazardous waste due to their heavy-metal content (nickel, vanadium, antimony); in the absence of regional regeneration facilities, they are often stockpiled onsite or disposed of in non-engineered landfills, risking groundwater contamination [26]. Petrochemical plants also discharge high volumes of spent caustic soda and phenolic compounds; without advanced tertiary treatment, these effluents raise the Chemical Oxygen Demand (COD) of receiving water bodies, creating "dead zones" in local river systems [27].

3) Circular Opportunity: Closing the Loop

Formalizing the informal waste-picking sector could feed rigid plastics (PET, HDPE) into mechanical recycling plants. The high volume of flexible, low-value plastics (sachets) makes the region a plausible candidate for pyrolysis plants, converting non-recyclable plastics into "pyro-oil" for use as refinery feedstock.

3.2. Policy Benchmarking: The Regulatory Disconnect

The comparative policy analysis (Section 2.2) reveals a significant implementation gap between Nigerian/Ghanaian environmental frameworks and the EU CEAP. While both countries possess the requisite environmental regulations, their effectiveness is severely limited by "isomorphic mimicry," a phenomenon whereby policies are adopted in form to satisfy external stakeholders or international agreements, but lack the political will, institutional capacity, or funding to function effectively in practice [28].

3.2.1. The Enforcement Gap: Gas Flaring and Penalties

Nigeria's Associated Gas Re-Injection Act of 1984 outlawed routine gas flaring, yet the practice continued for decades because the imposed penalties were often far cheaper than the cost of installing utilization infrastructure [29]. This regulatory laxity is compounded by a lack of transparency in measuring compliance, allowing International Oil Companies (IOCs) to treat regulations as a "matter of convenience, not necessity" [30]. Even the landmark Petroleum Industry Act (PIA) of 2021 and similar policies in Ghana designed to penalize flaring have struggled against the political power of the fossil fuel industry and a fundamental conflict between environmental protection and immediate economic revenue [31]. This contrasts sharply with the EU, where the Emissions Trading System (ETS) and carbon pricing create a clear, high financial disincentive for pollution.

3.2.2. Extended Producer Responsibility (EPR) and Funding Mechanisms

The transition to life-cycle thinking requires financial responsibility to shift from municipalities to producers, typically via Extended Producer Responsibility (EPR) schemes. Both Nigeria and Ghana have made legislative efforts, primarily for e-waste and packaging: Nigeria's National Environmental Regulations and the subsequent establishment of Producer Responsibility Organizations (PROs) are steps toward formalization [32], while Ghana's Hazardous and Electronic Waste Control and Management Act (Act 917) imposes obligations on producers [33]. Unlike the mandated and well-funded EPR systems in Europe, which set minimum targets for reuse and recycling, the West African schemes are often voluntary or under-enforced, lacking the mechanisms to enforce mandatory subscription and collect the levies needed to finance large-scale, environmentally sound collection and recycling infrastructure.

3.2.3. Benchmarking: End-of-Pipe vs. Life-Cycle Control

The core philosophical difference lies in the regulatory approach. Nigerian and Ghanaian policy focuses on treating or managing waste after it is produced (remediation, cleanup, modest fines) [34]. The European Green Deal and CEAP instead shift market incentives via instruments like the Carbon Border Adjustment Mechanism (CBAM), which imposes a carbon price on imports, including potential petrochemical products such as polymers and organic chemicals from countries with less stringent climate policies [35]. This effectively externalizes the EU's climate standards, forcing West African exporters to adopt greener production methods not just to comply with local law but to maintain market access. This proactive, market-linking approach is entirely absent in the current Nigerian and Ghanaian regulatory landscape, compounding the inertia against circularity.

3.3. Barrier Analysis

Transitioning to a circular model faces a "trilemma" of hurdles (financial, technical, and governance) classified using the procedure described in Section 2.3. The financial dimension is the most acute: the economic architecture of the Nigerian and Ghanaian oil and gas sectors is currently structured to favor linearity.

3.3.1. The Capital-Intensity Trap: High Cost of Green Finance

While global circular economy rhetoric focuses on technology availability, the primary hurdle in Nigeria and Ghana is the cost of capital. Implementing circular technologies such as pyrolysis plants for chemical recycling or VRUs for midstream terminals requires significant upfront foreign-currency (USD) capital expenditure. Local financing, however, is plagued by double-digit interest rates, often exceeding 25% - 30% in 2024/2025 [36]. Unlike the EU, where the Green Deal provides concessional financing, West African investors face a "Green Premium": the payback period for a mechanical recycling plant in Lagos is estimated at 5 - 7 years, compared to 3 years for a standard linear packaging plant, deterring private capital [37]. Because most circular technologies must be imported, fluctuations of the Naira and Cedi against the US Dollar also make the cost of maintaining spare parts for imported recycling machinery unpredictable, turning operational expenditure into a high-risk variable [38].

1) The Subsidy Paradox: a "Negative Carbon Tax"

The most pervasive structural barrier is the distortion created by fossil fuel subsidies, which effectively function as a negative carbon tax. By keeping the price of virgin fossil feedstock artificially low, subsidies inadvertently punish the recycling industry: in 2023/2024, the price of virgin PET resin occasionally dropped below the cost of producing high-quality food-grade recycled PET (rPET), owing to the correlation between resin prices and subsidized crude oil [7]. A recycler in Accra collecting, washing, and pelletizing waste plastics incurs costs related to labor, electricity, and water, while a virgin plastic producer benefits from subsidized energy inputs; without a fiscal equalizer, recycled materials struggle to compete on price, often trading at a 10% - 15% premium over virgin alternatives, limiting market uptake [9].

3.3.2. Technical and Infrastructure Barriers

1) Feedstock Purity and Collection Logistics

The primary technical barrier is not the lack of recycling technology but the lack of clean feedstock. In Nigeria and Ghana, Municipal Solid Waste is rarely separated at the source; organic waste, hazardous waste, and recyclables are comingled in a single stream, producing a contamination rate above 40% for plastics arriving at recovery facilities [39]. High contamination renders chemical recycling (pyrolysis) unfeasible, since the process requires strict feedstock specifications (low moisture, low PVC content) to avoid reactor fouling and hazardous chlorine emissions; even mechanical recycling requires water- and energy-intensive washing that drives up operational costs [40]. Unlike the EU's optimized collection routes, the region relies on an informal, decentralized network of waste pickers who achieve high recovery for high-value items (aluminum, PET) but lack the logistical capacity to recover low-value, high-volume petrochemical waste such as LDPE films, leading to significant material leakage [41].

2) The Energy-Manufacturing Nexus

Circular industries are energy-intensive: washing, shredding, melting, and extruding plastic requires continuous baseload power, which is fundamentally scarce in the region. Manufacturers in Nigeria report an average of 32.8 days of power outages per year [42]; for a recycling plant, a power cut is catastrophic, since molten plastic solidifying inside an extruder can require days of downtime and damage the screw mechanism. To mitigate this, firms rely on backup diesel generators, raising the cost of energy from ~\$0.12/kWh (grid) to over \$0.35 - \$0.40/kWh (diesel), an "energy tax" that destroys the thin profit margins of recycling ventures [43]. Many advanced recycling technologies imported from Europe are designed for stable 50 Hz grids; the voltage fluctuations common in regional grids frequently burn out the sensitive variable frequency drives (VFDs) and control systems of these machines, leading to high maintenance reliance on foreign technicians [44].

3.3.3. Governance Barriers: Regulatory Balkanization

1) The "End-of-Waste" Criteria Void

In the EU, specific regulations define when a waste product (e.g., crushed concrete or plastic pellets) ceases to be "waste" and becomes a "product." Nigeria and Ghana lack this legal distinction; consequently, high-value secondary raw materials such as pyrolysis oil derived from waste plastic are often legally classified as "hazardous waste" rather than "fuel" by customs officials [45]. This classification subjects these materials to the Prior Informed Consent (PIC) procedure under the Basel Convention, delaying cross-border shipments by 6 - 12 months and undermining the commercial viability of regional recycling hubs [46].

2) The Bamako Convention Paradox

West Africa operates under the Bamako Convention, which is significantly stricter than the global Basel Convention. Article 4 strictly bans the import of hazardous wastes into Africa; while designed to prevent toxic dumping, this blanket ban inadvertently criminalizes the import of recyclable hazardous materials, such as spent petrochemical catalysts or lead-acid batteries, from neighboring countries [47]. A modern battery recycling plant requires roughly 50,000 tonnes of feedstock annually to be profitable, more than any single West African nation generates alone, and the Bamako Convention effectively blocks the regional consolidation of feedstock required to reach this scale, trapping the region in a state of permanent under-capacity [48].

3) Permitting Paralysis and Tariff Misalignment

In Ghana, exporting recyclable waste requires "Written Authorization" from the Minister of Environment, acting on advice from the EPA (Act 917); obtaining this permit, along with required "Transit State Consents" for landlocked neighbors such as Burkina Faso, can take upwards of 30 - 60 working days, creating bottlenecks that degrade organic-rich waste streams [49]. The ECOWAS Common External Tariff (CET) also often works against circularity: import duties on virgin plastic resins are sometimes lower (5% - 10%) than duties on the specialized machinery required to recycle them (up to 20% for "industrial machinery"), effectively subsidizing the linear economy while taxing the circular transition [50].

3.4. Estimated Value of the Secondary-Materials Market

Using the approach set out in Section 2.4, **Table 2** aggregates the currently quantifiable secondary-materials value identified in Section 3.1. Two known waste streams, refinery sludge and spent FCC catalysts, are excluded from the total because the reviewed literature reports their composition and hazard classification but not the tonnage or price data required for a defensible valuation; their exclusion means the total below is conservative.

This indicative range of roughly $2.1 - 2.4 billion per year from currently quantifiable streams alone supports the abstract's reference to a multibillion-dollar secondary market, while making clear that (i) it is a bottom-up illustrative estimate rather than a formal market study, (ii) it excludes at least two known but currently unquantifiable waste streams, and (iii) it is therefore likely conservative. This estimate, its assumptions, and its exclusions are revisited as a limitation in Section 7.2.

4. Strategic Roadmap: From Theory to Implementation

Based on the hotspots and barriers identified in Section 3 and prioritized using the criteria in Section 2.3, we propose a phased implementation strategy. This roadmap goes beyond generic interventions to leverage existing regional pilot projects and financial instruments.

4.1. Phase 1: Short-Term (0 - 3 Years)—Remediation and Monetization

- Objective: stop value leakage through the immediate commercialization of waste streams.
- Key Intervention: the "Flare-to-Market" Model.
    - Action: Operationalize the Nigerian Gas Flare Commercialization Programme (NGFCP): In 2024, the NUPRC awarded 49 flare sites to 42 third-party investors [51]. The immediate priority is deploying skid-mounted Gas-to-Liquids (GTL) units at these sites to convert waste gas into diesel or LPG for local markets.
    - Case Example: Genser Energy (Ghana). Genser has built 425 km of private gas pipelines to power gold mines (e.g., Gold Fields Tarkwa), using gas that would otherwise be stranded. This "captive power" model should be replicated for industrial zones in Lagos and Ogun State [52].
- Financial Enabler: Sovereign Green Bonds. Nigeria's Series III Green Bond should be specifically ring-fenced to finance the CAPEX of flare-capture technologies, lowering the cost of capital from ~28% (commercial bank rate) to single digits.

4.2. Phase 2: Medium-Term (3 - 7 Years)—Systemic Symbiosis

- Objective: Institutionalize circularity through physical clustering of industries.
- Key Intervention: The "Jomoro" Symbiosis Model.
    - Action: Design the Jomoro Petroleum Hub (Ghana) not merely as a refinery complex, but as an Eco-Industrial Park. The $12 billion project should integrate a Waste-to-Energy (WtE) plant where refinery sludge and municipal plastic waste from the Western Region power the facility's 24-hour operations [53].
    - Action: Polymer-Cement Coupling. Co-locate cement plants (e.g., Dangote Cement) near petrochemical refineries. The refinery's sulfur byproduct is a critical input for gypsum production used in cement, while the cement kiln can safely co-process non-recyclable refinery hazardous waste at high temperatures (>1400˚C).
- Policy Lever: Tax Holidays for "Symbiotic" Zones. Companies operating within designated eco-parks should receive a 5-year tax holiday on corporate income tax, conditional on proving that they utilize at least 30% secondary (waste) feedstock.

4.3. Phase 3: Long-Term (7 - 10+ Years)—Closing the Loop (Molecular Recycling)

- Objective: decouple sector growth from virgin fossil extraction.

- Key Intervention: Green Hydrogen and Chemical Recycling.

Action: Transition from "grey" to "green" hydrogen for refinery hydro-processing: Nigeria's National Hydrogen Policy (drafted with German support/H2-Diplo) identifies the potential to use solar-generated hydrogen to desulfurize crude oil, lowering the carbon intensity of West African exports by 40% [54].

Action: Feedstock substitution should also be pursued: major players such as Indorama Eleme Petrochemicals have committed to using 23% recycled feedstock by 2030 [55]; achieving this requires investment in pyrolysis plants that convert "sachet economy" LDPE waste into pyro-oil, which can be cracked alongside crude oil at the Dangote Refinery.

5. Discussion

This study set out to map the circular economy potential within Nigeria and Ghana's petrochemical sector. The resulting roadmap suggests that while technical pathways (e.g., gas-to-power, chemical recycling) are established, systemic implementation remains fraught with challenges. This section discusses the implications of the proposed roadmap in relation to the identified barriers and policy gaps.

5.1. The Policy-Implementation Gap: Beyond "Isomorphic Mimicry"

The policy benchmarking (Section 3.2) revealed a stark contrast between the EU's integrated framework and the fragmented Nigerian/Ghanaian regulatory landscape. A critical finding is the prevalence of "isomorphic mimicry," where regional governments adopt the form of global best practice (such as plastic bans) without the function (enforcement mechanisms or infrastructure) [28]. Unlike the EU, where the CEAP is backed by Green Deal financing, Nigerian and Ghanaian policies often lack fiscal teeth: while Nigeria's PIA criminalizes flaring, penalties have historically been tax-deductible or lower than the commercial cost of gas reinjection equipment. The roadmap's Phase 1 argues that regulation alone is insufficient; it must be coupled with commercialization of waste streams. As long as the cost of compliance exceeds the cost of violation, circularity will remain theoretical.

5.2. The Subsidy Paradox and Economic Viability

The barrier analysis (Section 3.3) identified financial hurdles as the primary obstacle. A structural impediment specific to this context is the prevalence of fossil fuel subsidies, which artificially lower the cost of virgin fossil-based fuels and feedstocks, unintentionally undermining the market for secondary (recycled) materials [8]. A plastic recycler in Ghana competing against virgin plastic production faces a market where virgin feedstock is subsidized at the refinery gate. This study argues that the roadmap's success relies on a "fiscal shift": moving subsidies away from consumption and toward infrastructure development for the Eco-Industrial

Parks proposed in Phase 2. Without leveling the playing field, recycled petrochemical products cannot compete on price.

5.3. Industrial Symbiosis as the Gateway

The most promising intervention identified is Industrial Symbiosis (Phase 2). Given the region's logistical challenges (poor road networks and grid instability), geographic clustering offers a resilience strategy. By co-locating refineries, petrochemical plants, and cement manufacturers, waste outputs from one become inputs for another in situ, bypassing the need for complex national transport grids. This aligns with findings from comparable emerging economies in Southeast Asia, where eco-industrial parks reduced shared energy costs by up to 20% [56]. This approach reframes the "waste problem" as an "efficiency solution," making circularity adoption a business decision rather than only an environmental compliance burden.

5.4. Governance and Cross-Border Trade

Finally, the roadmap highlights the necessity of a supranational approach. Pollution in the petrochemical chain is transboundary; marine plastic litter from the Gulf of Guinea affects the entire coastline. Currently, the lack of harmonized "End-of-Waste" criteria hinders the movement of recyclable materials between ECOWAS nations: if Ghana has surplus recycling capacity and Nigeria has surplus plastic waste, regulatory friction prevents the transfer. We suggest that a unified "ECOWAS Circularity Standard" is a prerequisite for achieving the economies of scale necessary for Phase 3 (advanced chemical recycling), though it is consistent with the scope stated in Section 1.1. This specific recommendation extends beyond the Nigeria/Ghana evidence base and should be treated as a hypothesis for further regional research rather than a finding.

6. Conclusions

The transition from a linear to a Circular Economy (CE) in Nigeria and Ghana's oil and gas sector represents a complex but unavoidable paradigm shift. This study has demonstrated that the region's current "take-make-dispose" model is economically inefficient and environmentally unsustainable. By mapping waste hotspots against explicit prioritization criteria (Section 2.3), we identified that the greatest leakage of value occurs in the upstream (flaring) and downstream (single-use plastics) segments.

The roadmap developed in this research offers a pragmatic path forward. It moves beyond the idealistic expectation of immediate transformation, proposing a phased evolution instead. The initial focus on "stopping the bleeding" via gas reinjection and flaring penalties addresses the most immediate emission sources. The progression to industrial symbiosis leverages the region's specific constraint, lack of infrastructure, by turning proximity into an asset through eco-industrial parks. The long-term goal of closing the loop through chemical recycling envisions a future in which waste is treated as a strategic resource.

Ultimately, the success of this roadmap relies on a fundamental fiscal shift. Governments must redirect financial flows from subsidizing consumption (fuel subsidies) to subsidizing production efficiency (recycling infrastructure). Without this economic realignment, circular technologies will remain niche experiments rather than industry standards.

7. Limitations and Future Research

While this study provides a strategic framework, it is subject to specific limitations that future research should address.

7.1. Data Scarcity in the Informal Sector

A significant portion of waste management in Nigeria and Ghana is conducted by the informal sector (waste pickers). Due to the unregulated nature of this activity, accurate data on plastic waste volumes and recovery rates are scarce. This study relied on aggregated data from institutional reports, which may underestimate the true scale of waste generation. Future studies should employ primary field data collection to quantify the contribution of the informal sector.

7.2. Estimation and Economic Volatility

The secondary-market estimate in Section 3.4 is a bottom-up, order-of-magnitude calculation built on institutional figures from different base years and, in the case of plastics, an illustrative recovery-uplift assumption rather than a market survey; it should be read as an indicative range, not a forecast, and excludes at least two known waste streams (sludge, spent catalysts) for which regional tonnage data could not be identified. Separately, the economic viability of the proposed circular interventions (e.g., plastic-to-fuel) is highly sensitive to global crude oil prices: when oil prices fall, virgin plastic becomes cheaper than recycled plastic. This study assumes a stable baseline for energy prices; Future financial modeling should incorporate sensitivity analyses of oil-price volatility and update the estimates in **Table 2** using primary tonnage data on sludge and spent-catalyst streams.

7.3. Scope of Technology and Geography

This roadmap focused heavily on mature technologies (mechanical recycling, gas-to-power); emerging technologies such as biological degradation of plastics (using enzymes) or Direct Air Capture (DAC) in refineries were considered outside the scope of short-to-medium-term feasibility for the region and were not evaluated. As these technologies mature, the roadmap should be revisited. Geographically, as noted in Section 1.1, the evidence base is drawn from Nigeria and Ghana; extending the roadmap's conclusions to other ECOWAS states, or treating the proposed "ECOWAS Circularity Standard" (Section 5.4) as more than a hypothesis, would require replicating the SLR and policy benchmark with country-specific data for those states.

Author Contributions

P.J.Y.: Conceptualization, methodology, investigation, formal analysis, writing—original draft, writing—review & editing. J.J.A.A., L.K.S. and R.V.A.: Funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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