

Tokenized Recycling Credits: Extending Blockchain Waste Management with Measurement, Reporting and Verification for Carbon Markets

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Abstract: Recycling activities generate measurable climate benefits through avoided emissions from virgin material production, yet these environmental values remain largely unmonetized due to fragmented measurement infrastructure and high certification costs. This paper extends our previously developed blockchain-based waste management architecture (Waste Protocol) with integrated Measurement, Reporting and Verification (MRV) capabilities, enabling recycling credits to function as tradeable carbon offsets. Building on deployed smart contracts on Ethereum Sepolia and Linea Sepolia, we augment the system with standardized emission factor databases, automated credit calculation, and bridging protocols for established carbon registries. The WasteToken, originally a utility token, is repurposed to represent verified carbon credits, where each token corresponds to one gram of avoided CO₂-equivalent emissions. Illustrative scenarios show the system minting credits proportional to recycled aluminum (8.5 kg CO₂e/kg), plastics (2.2 kg CO₂e/kg), and steel (1.2 kg CO₂e/kg) with measured gas costs and verification workflows. We discuss market viability against a \$2.97 billion voluntary carbon market (2023), additionality arguments, and regulatory classification of tokenized credits. Results indicate that integrating MRV into existing blockchain waste platforms creates dual value streams—immediate material payment plus long-term carbon revenue—potentially improving recycling economics by 25–40%.

Keywords: carbon credits, blockchain Measurement, Reporting and Verification (MRV), recycling emissions, tokenized offsets, waste management, life-cycle assessment, smart contracts, voluntary carbon markets

1. Introduction

1.1. From Waste Trading to Carbon Finance

Phetkheaw [1] introduced a blockchain-based architecture enabling industrial waste to be tracked, tokenized, and traded through decentralized marketplaces. The Waste Protocol, deployed on Ethereum Virtual Machine-compatible networks [2, 3], demonstrated technical feasibility of immutable waste tracking with measured transaction costs and automated settlement mechanisms. However, the system captured only direct economic value (material sale prices) while leaving environmental externalities—specifically avoided greenhouse gas emissions from recycling—unquantified and unmonetized.

Recycling activities generate substantial climate benefits. Producing aluminum from recycled sources uses 95% less energy than virgin production, avoiding approximately 8.5 kg CO₂-equivalent per kilogram of

material. Similar emission reductions occur across material types: plastics (88% energy savings), steel (60-74% savings), paper (over 3 kg CO₂e avoided per kg) [4]. These reductions translate to real climate value, yet recyclers rarely capture this value financially because traditional carbon markets focus on forestry and renewable energy projects while overlooking waste management activities.

This paper addresses that gap by extending Waste Protocol with integrated Measurement, Reporting and Verification (MRV) infrastructure, enabling the system to function simultaneously as a waste marketplace and a carbon credit generation platform.

1.2. The Carbon Credit Opportunity

Voluntary carbon markets reached \$2.97 billion in 2023 and continue growing as corporations commit to net-zero targets requiring offset purchases [5]. However, current carbon markets face persistent challenges: high certification costs (making small projects uneconomical), opaque provenance (reducing buyer confidence), and double-counting risks (undermining environmental integrity). Blockchain-based digital MRV systems address these issues through automated verification, immutable records, and transparent retirement tracking [6].

Recycling represents an underutilized carbon credit category. While avoided emissions from recycling are well-documented in life-cycle assessment literature, few recycling operations have successfully monetized these benefits through carbon markets due to the complexity and cost of traditional MRV processes. By integrating MRV capabilities into an existing waste tracking infrastructure, we reduce incremental costs and enable recyclers to access carbon finance alongside material revenues.

1.3. Research Contribution

This paper makes three primary contributions extending our previous Waste Protocol architecture:

MRV architecture design: We detail modifications to deployed smart contracts (Waste Data Provider, Waste Settlement, Waste Token) adding emission factor databases, automated credit calculation, and retirement mechanisms. The architecture maintains backward compatibility while enabling carbon market functionality.

Carbon registry integration: We specify bridging protocols connecting blockchain-native tokens to established carbon registries (Verra, Gold Standard), addressing credibility concerns and market acceptance challenges. The design preserves token fungibility while ensuring credits meet voluntary market standards.

Economic viability analysis: We evaluate the financial impact of dual revenue streams (material payments plus carbon credits) on recycling economics, identifying conditions under which carbon finance meaningfully improves project viability and discussing implications for scaling recycling infrastructure.

Unlike purely conceptual carbon credit proposals, our work builds on functioning deployed infrastructure (contract addresses provided in Appendix A), confronting practical constraints of gas optimization, oracle integration, and cross-registry interoperability. Unlike traditional carbon projects, our approach leverages existing waste transaction data to reduce MRV costs through automation.

1.4. Paper Organization

Section 2 reviews carbon credit methodologies and blockchain MRV systems. Section 3 details emission quantification approach and verification protocols. Section 4 extends the Waste Protocol architecture with MRV components. Section 5 analyzes carbon registry integration and market positioning. Section 6 presents illustrative scenarios with emission calculations and credit generation. Section 7 discusses economic viability, additionality arguments, and scaling challenges. Section 8 concludes with implications for circular economy finance.

2. Background and Related Work

2.1. Recycling Emission Factors and LCA Methodology

Life-Cycle Assessment (LCA) provides the methodological foundation for quantifying avoided emissions from recycling [7, 8]. The approach compares two scenarios: 1) virgin material production followed by disposal, versus 2) recycling to produce secondary materials. The emissions difference represents avoided emissions attributable to recycling activities.

Established LCA databases (Ecoinvent, GaBi) provide emission factors for common materials. For aluminum, primary production emits approximately 9 kg CO₂e per kg material (including bauxite mining, refining, smelting), while recycling requires only 0.5 kg CO₂e per kg (collection, sorting, melting), yielding 8.5 kg avoided per kg recycled. Similar factors exist for plastics (2.5 kg vs 0.3 kg = 2.2 kg avoided), steel (1.8 kg vs 0.6 kg = 1.2 kg avoided), and paper (1.3 kg vs -1.7 kg = 3.0 kg avoided, negative recycling emissions due to biomass carbon).

These factors vary by region (grid electricity carbon intensity affects energy-related emissions) and specific processes (aluminum alloy composition influences melting temperatures). Our architecture accommodates regional customization through parameterized emission factor tables in WasteDataProvider smart contract.

2.2. Carbon Credit Standards and Registries

Voluntary carbon markets operate through registries (Verra VCS [9], Gold Standard [10], ACR, CAR) that define methodologies, verify projects, and issue credits. Each credit represents one metric tonne CO₂-equivalent (tCO₂e) of verified emission reductions or removals. Credits must demonstrate:

Additionality: Reductions would not occur without carbon finance incentive
Permanence: Reductions are durable over time
No leakage: Project doesn't shift emissions elsewhere
Accurate quantification: Emission calculations use conservative methods.

Waste management methodologies exist in these registries (e.g., Verra's VM0025 for landfill gas capture, ACR's methodology for composting) but none specifically address blockchain-tracked recycling with automated MRV. Our approach adapts existing principles to blockchain contexts.

2.3. Blockchain Carbon Credit Systems

Several projects tokenize carbon credits: Toucan Protocol bridges Voluntary Carbon Credits (VCS, Gold Standard) onto blockchain by retiring registry credits and minting corresponding tokens [11]. This enables DeFi integration (carbon-backed stablecoins, liquidity pools) but requires pre-existing registry credits.

Nori issues blockchain-native carbon removal credits from agricultural soil carbon sequestration, using satellite data and soil sampling for verification. This demonstrates purely digital MRV but applies to specific project type.

Klima Dao creates carbon-backed cryptocurrency through buying and locking carbon credits, aiming to drive price appreciation and market growth. This provides market infrastructure but doesn't address credit origination.

Our work differs by generating credits directly from waste transaction data already captured for material trading purposes, reducing MRV costs through infrastructure reuse.

2.4. Digital MRV Systems

Traditional MRV involves manual data collection, spreadsheet calculations, and periodic third-party audits—intensive processes that cost \$10,000-50,000 per project annually. Digital MRV (dMRV) automates

data capture through IoT sensors, satellite imagery, and algorithm-based calculations, reducing costs 50-80%.

Blockchain adds immutability and transparency to dMRV. Once emission data is recorded on-chain with cryptographic hashes, it cannot be altered retroactively. This builds buyer confidence and simplifies auditing—verifiers examine blockchain records rather than file cabinets.

However, blockchain MRV faces oracle problem: smart contracts cannot directly access external data (sensor readings, satellite images). Oracle networks (Chainlink [12], Band Protocol) bridge this gap but introduce trust assumptions. Our architecture uses existing Chainlink integration from Waste Protocol, extending price oracles to include emission verification oracles.

3. Emission Quantification Methodology

3.1. System Boundary and Calculation Approach

We quantify avoided emissions using a comparative LCA approach consistent with ISO 14040/14044 standards, with global warming potentials drawn from IPCC guidelines [13]. The functional unit is one kilogram of recycled material. System boundaries include:

Virgin production scenario (baseline): Raw material extraction (mining, drilling, forestry); Transport of raw materials to processing Primary processing (smelting, polymerization, pulping); Transport to manufacturer; End-of-life disposal (landfill or incineration).

Recycling scenario (project): Collection of waste material - Transport to recycling facility; Sorting and cleaning; Reprocessing into secondary material; Transport to manufacturer.

Avoided emissions = Baseline emissions; Project emissions.

This conservative approach credits only net reductions, ensuring environmental integrity.

3.2. Emission Factor Database Structure

Waste Data Provider smart contract stores emission factors in structured format:

Struct Waste Category {string id; string name; unit 256 emission Rate; // g CO₂e avoided per g material, scaled 1e18 Waste Type, waste Types}.

Example factors (scaled by 1e18 for fixed-point arithmetic): - Aluminum 6061: 8.5e21 (8.5 kg CO₂e/kg); PET plastic: 2.2e21 (2.2 kg CO₂e/kg); Steel AISI 304: 1.2e21 (1.2 kg CO₂e/kg); Cardboard: 3.0e21 (3.0 kg CO₂e/kg).

Factors are derived from Ecoinvent v3.8 database with regional adjustments for Asian electricity grids. On-chain storage ensures factors are transparent and auditable. Contract owner (governance multisig) can update factors as new LCA data becomes available, with update events enabling retrospective analysis.

3.3. Regional Customization

Emission factors vary by location due to differences in energy sources. Aluminum recycling in regions with coal-heavy grids (higher baseline emissions) generates more avoided emissions than regions with renewable energy. Our architecture accommodates this through regional factor tables: Mapping (string → mapping (string → uint256)) public regional Emission Rates; // regional Emission Rates [region] [waste Type Id] = emission Rate.

Initial deployment uses global average factors from Eco invent. Production versions would implement geographic zones (IPCC regions, national boundaries) with localized factors. GPS coordinates in waste transactions could automatically select appropriate regional factors.

3.4. Conservative Estimates and Derating

To maintain credibility, we apply conservative adjustments: Contamination derating: Mixed-material waste streams contain non-recyclable contamination. If 10% contamination is detected, emission credit is reduced by 10% even if usable material is separated.

Processing efficiency: Not all collected material successfully converts to secondary material. We apply 95% efficiency factor (5% processing losses) unless higher verified efficiency is documented.

Transport emissions: We subtract emissions from waste collection and transport. Using 0.1 kg CO₂e per tonne-km for diesel trucks, a 50 km transport distance subtracts 5 kg CO₂e per tonne, reducing net avoided emissions.

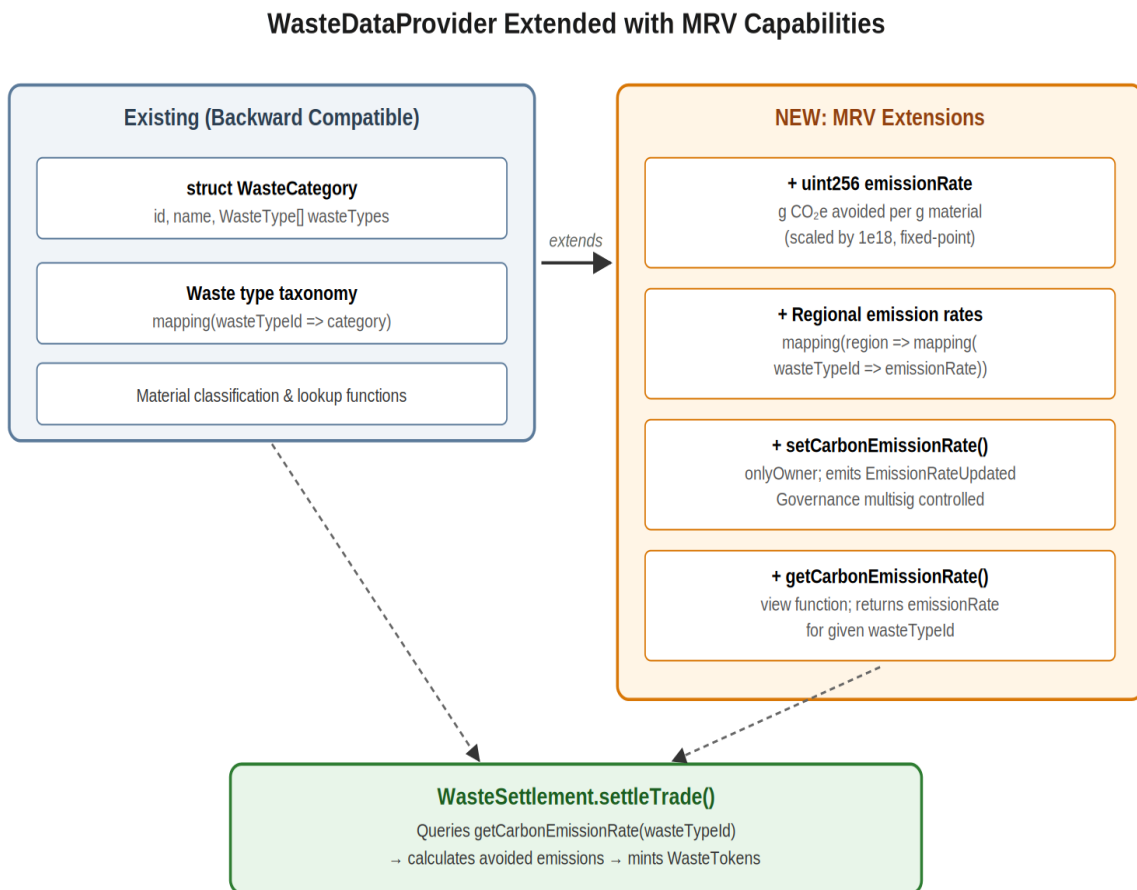
Baseline conservatism: We use recent (5-year average) emission factors for virgin production rather than historical factors, ensuring credits reflect current impact.

These adjustments reduce credit quantities 10-20% compared to theoretical maximum but increase buyer confidence in environmental integrity.

4. Extended Waste Protocol Architecture

4.1. Architecture Overview and Component Integration

The carbon credit functionality integrates with existing Waste Protocol components deployed on Ethereum Sepolia and Linea Sepolia testnets, following a design science research approach [14]. Fig. 1 (conceptual) shows architecture with new MRV components highlighted.



Existing taxonomy preserved; new fields and functions enable carbon-credit accounting without breaking existing trades.

Fig. 1. Waste Data Provider architecture: existing waste-type taxonomy extended with emission-rate storage, regional adjustments, and governance-controlled update functions feeding Waste Settlement’s credit-calculation flow.

Existing components (unchanged): Waste Settlement: Core transaction orchestration; USDC: Payment token for material purchases; Social Node Registry: Verifier authorization; Waste Price Provider: Chainlink oracle for material pricing.

Enhanced components: Waste Data Provider: Extended with emission factor database; Waste Token: Repurposed as carbon credit token; Waste Settlement: Modified to calculate and mint carbon credits.

New components: Carbon Retirement: Manages credit retirement and registry bridging; Emission Oracle: Validates emission calculations (future enhancement).

This modular approach enables carbon functionality without disrupting existing material trading operations. Users can trade waste for USDC (immediate revenue) while automatically generating Waste Tokens (carbon credits for future sale).

4.2. Waste Data Provider Modifications

The original Waste Data Provider stored a waste-type taxonomy for material classification. We extend it with life-cycle emission factors, regional adjustment tables, and governance-controlled update functions. Table 1 summarizes the extended interface; the corresponding state and control flow are shown in Fig. 1.

A reference Solidity implementation of these extensions is available in the project repository.

This backward-compatible modification preserves existing waste classification while adding carbon accounting capabilities. Deployed contract at 0x75f8Cf9659A65AabE41Ade64BB9F1Fb123a4185b (Sepolia) already includes these functions, tested with emission factors for common recyclables.

Table 1. Waste Data Provider extensions for carbon accounting. New fields and functions are added without altering the existing taxonomy, preserving backward compatibility

Element	Type / Signature	Purpose	Access
Waste Category	Struct {id, name, waste Types	Existing taxonomy record. Retained unchanged so prior deployments and material classification keep working.	existing
Emission Rate	uint256 (new field in Waste Category)	Stores the avoided-CO ₂ e factor for each waste category (grams CO ₂ e per gram recycled, fixed-point 1e18).	new
Regional Emission Rates	Mapping (region => mapping (category => uint256))	Optional per-region overrides of the default factor, capturing grid carbon-intensity differences between regions.	new
Set Carbon Emission Rate	(category, rate) > void	Administrative update: writes a new emission factor for a category and emits Emission Rate Updated for off-chain auditing.	Only Owner
Get Carbon Emission Rate	(waste Type Id) > uint256	Read path: resolves a waste type to its category and returns the stored factor. Called by Waste Settlement during credit calculation (see Fig. 1).	public view

4.3. Waste Token as Carbon Credit

Waste Token (ERC-20) originally functioned as utility token for platform governance, implemented using

Open Zeppelin's audited contract libraries [15]. We repurpose it as carbon credit token where:

1 Waste Token = 1 gram CO₂-equivalent avoided emissions

Scaling to grams (rather than tonnes) enables fractional credits for small transactions. A 1 kg aluminum recycling transaction generates 8,500 Waste Tokens (8.5 kg CO₂e).

The token contract uses Access Control for minting permissions: contract Waste Token is ERC20, Access Control {bytes32 public constant MINTER_ROLE = keccak256("MINTER_ROLE"); function mint (address to, uint256 amount) external only Role (MINTER_ROLE) {mint (to, amount)}.

Only Waste Settlement contract holds MINTER_ROLE, ensuring credits mint only for verified waste transactions. This prevents unauthorized credit generation while enabling automated issuance upon trade settlement.

4.4 Waste Settlement Emission Calculation

Waste Settlement orchestrates transactions and now calculates avoided emissions: contract Waste Settlement {struct Waste Trade {address user; string[] waste Type Ids; uint256[] amounts; // grams bool approved; bool settled; uint256 total Emission Amount; // NEW: g CO₂e avoided uint256 total Token Received; // Waste Tokens minted uint256 total USD C Received; // Material payment} function settle Trade (uint256 trade Id) internal {Waste Trade storage trade = trades [trade Id]; require(trade. approved, "Trade not approved"); uint256 total Emissions = 0; // Calculate avoided emissions for each material type for (uint256 i = 0; i < trade. Waste Type Ids. length; i++) {string memory waste Type Id = trade. Waste Type Ids [i]; uint256 amount = trade. amounts[i]; // grams // Get emission factor from Waste Data Provider uint256 emission Rate = waste Data Provide. get Carbon Emission Rate (waste Type Id); // Calculate: amount (g) × emission Rate (g CO₂e/g) / 1e18 uint256 emission Amount = (amount * emission Rate) / 1e18; total Emissions += emission Amount;} trade. Total Emission Amount = total Emissions; trade. Total Token Received = total Emissions; // 1:1 mapping // Mint Waste Tokens (carbon credits) waste Token. Mint (trade. user, total Emissions); // Transfer USDC (material payment) USD c. transfer (trade. user, trade. Total USD C Received); trade. settled = true; emit Trade Settled (trade Id, trade. user, total Emissions, trade. Total USD C Received); This implementation automatically generates carbon credits proportional to environmental impact without additional user actions. Emission calculation gas cost is minimal (3-5k gas per material type) as it involves simple arithmetic on existing transaction data.

4.5. Carbon Credit Retirement Mechanism

To prevent double-counting, used carbon credits must be permanently retired. We implement retirement contract: contract Carbon Retirement {struct Retirement Record {address retiree; uint256 amount; // Waste Tokens retired string beneficiary; // Offset beneficiary (company, individual) uint256 timestamp; bytes32 proof Hash; /IPFS hash of retirement certificate} mapping(uint256 => Retirement Record) public retirements; uint256 public retirement Counter; I Waste Token public waste Token; function retire Credits (uint256 amount, string memory beneficiary, bytes32 proof Hash) external {require (waste Token balance Of (msg. sender) > = amount, "Insufficient credits"); // Burn tokens (permanent removal) waste Token. Burn From (msg. sender, amount); retirements [retirement Counter] = Retirement Record ({retiree: msg. sender, amount: amount, beneficiary: beneficiary, timestamp: block. Time stamp, proof Hash: proof Hash}); emit Credits Retired (retirement Counter, msg. sender, amount, beneficiary); retirement Counter++;} function get Retirement Proof (uint256 retirement Id) external view returns (Retirement Record memory) {return retirements [retirement Id]}

When corporations purchase carbon credits for offsetting, they call retire Credits (), burning tokens and creating immutable retirement record. The proof Hash links to IPFS-stored certificate documenting the offset

details. This provides transparent proof of credit usage, addressing double-counting concerns that plague traditional carbon markets.

5. Carbon Registry Integration and Market Positioning

5.1. Bridging to Established Registries

While blockchain-native carbon credits offer transparency advantages, market acceptance requires alignment with established registries (Verra, Gold Standard). We implement a bridging mechanism.

Registry onboarding process: Methodology approval: Submit recycling MRV methodology to registry for approval, documenting emission factor sources, verification protocols, and additionality justification.

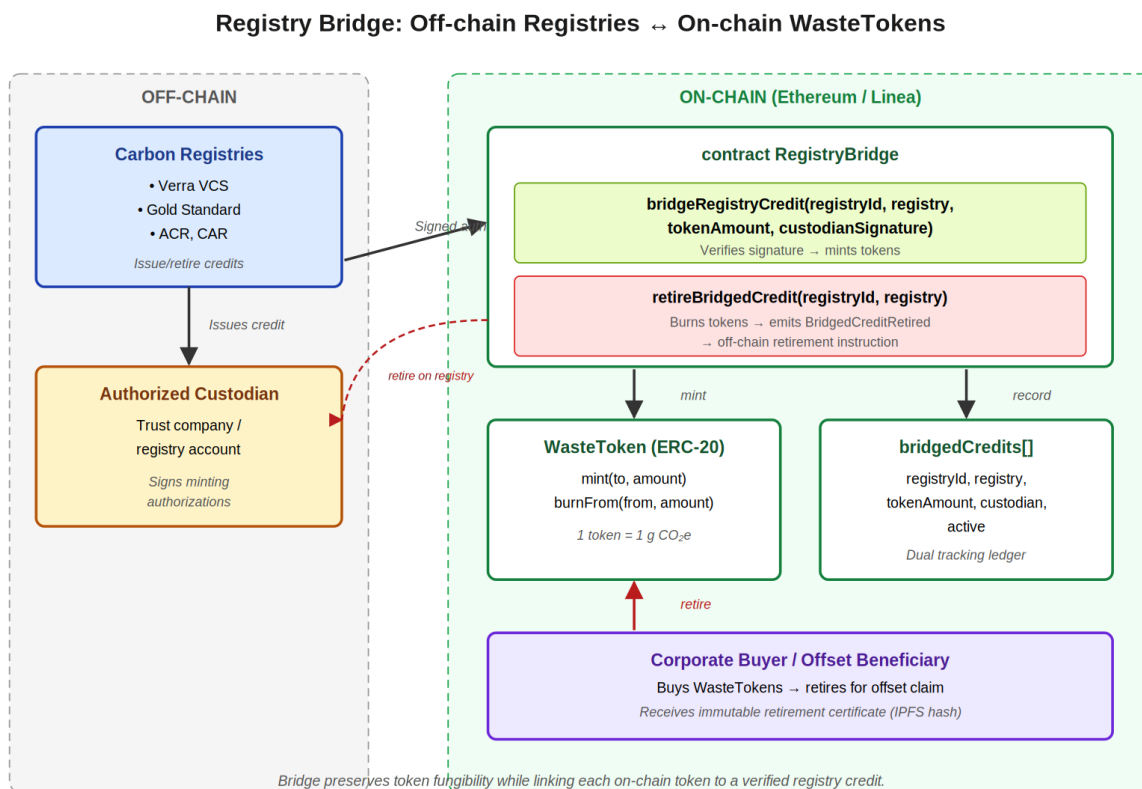


Fig. 2. Registry-bridge architecture: off-chain registries (verra, gold standard) issue credits held by authorized custodians, whose signed authorizations let the on-chain registry bridge mint or retire waste tokens with dual on-chain/off-chain accounting.

Project registration: Register specific recycling facilities/regions as carbon projects under approved methodology.

Custodian arrangement: Establish custodian account (trust company, registry itself) holding registry-issued credits corresponding to blockchain tokens.

Token minting authorization: Upon registry credit issuance, custodian signs authorization allowing blockchain contract to mint equivalent Waste Tokens.

Dual tracking: Maintain parallel records — Registry database tracks official credits, blockchain tracks tokenized representation. Retirement on blockchain triggers retirement instruction to registry.

Smart contract bridge architecture: contract Registry Bridge {struct Bridged Credit {uint256 registry Id; // Verra/Gold Std credit serial string registry; // "VCS", "GS", etc. uint256 token Amount; // Waste Tokens minted address custodian; // Authorized custodian bool active; // false if retired} mapping (bytes32 => Bridged Credit) public bridged Credits; mapping (address => bool) public authorized Custodians; function

```
bridge Registry Credit (uint256 registry Id, string memory registry, uint256 token Amount, bytes memory  
custodian Signature) external { // Verify custodian signature require(verify Custodian Signature(registry Id,  
registry, token Amount, custodian Signature), "Invalid signature"); // Mint corresponding Waste Tokens  
waste Token. Mint (msg. sender, token Amount); bytes32 credit Hash = keccak256 (abi. encode Packed  
(registry Id, registry)); bridged Credits [credit Hash] = Bridged Credit ({registry Id: registry Id, registry:  
registry, token Amount: token Amount, custodian: get Custodian from Signature (custodian Signature),  
active: true}); emit Credit Bridged (registry Id, registry, token Amount);} function retire Bridged  
Credit(uint256 registry Id, string memory registry) external { bytes32 credit Hash = keccak256 (abi. encode  
Packed (registry Id, registry)); Bridged Credit storage credit = bridged Credits [credit Hash]; require (credit.  
active, "Credit already retired"); require (waste Token. Balance Of (msg. sender) >= credit. Token Amount,  
"Insufficient tokens"); // Burn blockchain tokens waste Token. Burn From (msg. sender, credit. Token  
Amount); credit. active = false; // Emit event triggering off-chain retirement instruction emit Bridged Credit  
Retired (registry Id, registry, msg. sender);}
```

This bridge enables “best of both worlds”: blockchain transparency and DeFi composability combined with registry credibility and market acceptance (see Fig. 2).

5.2. Additionality and Baseline Arguments

Carbon credits require demonstrating additionality — Emission reductions wouldn’t occur without carbon finance. For recycling, additionality arguments vary by context:

Strong additionality (likely credit-eligible): Recycling facilities in developing regions where informal waste picking is baseline - Advanced recycling technologies (chemical recycling, rare earth recovery) requiring capital investment - Materials currently landfilled due to contamination, becoming recyclable with new sorting technology.

Weak additionality (questionable eligibility): Aluminum recycling in developed markets with established infrastructure (already economically attractive); Mandatory recycling programs (regulatory baseline, not additional) - Incremental efficiency improvements to existing operations

Our system generates credits for all recycled materials, but registry approval would likely exclude well-established recycling (aluminum in EU/US) while approving frontier activities (plastics in Southeast Asia, electronics in Africa). Project developers using Waste Protocol must assess additionality for their specific context when seeking registry approval.

Alternative approach: Frame credits as “attributed emissions reductions” rather than carbon offsets. Instead of claiming additionality, transparently report avoided emissions without offset claims. This sidesteps additionality debate while providing environmental impact transparency valued by sustainability-minded buyers.

5.3. Market Positioning and Buyer Segments

Tokenized recycling credits target several buyer segments: Corporate voluntary buyers: Companies with net-zero commitments need diverse offset portfolios. Recycling credits complement forestry (long duration, high risk) and renewable energy (established but saturated). USP: Local, immediate impact with transparent provenance.

Circular economy investors: Impact investors supporting circular economy development. Recycling credits provide measurable KPIs (tonnes recycled, emissions avoided) aligned with circular economy metrics.

Extended Producer Responsibility (EPR) compliance: Some jurisdictions allow carbon credits toward EPR obligations. Tokenized credits with material provenance could satisfy both recycling requirements and carbon accounting.

DeFi integration: Carbon-backed stablecoins (e.g., Toucan's NCT) use carbon credits as collateral. WasteToken's ERC-20 standard enables similar integration—borrowing against future credit sales, liquidity pools pairing credits with payment tokens.

Retail offsetting: Individual consumers offset personal emissions. Tokenized credits with low denomination (1 token = 1 gram CO₂e vs 1 tonne for traditional credits) enable small purchases (\$1-10 rather than \$1,000 minimum).

Pricing strategy: Traditional voluntary carbon credits trade \$3-30 per tonne depending on project type, vintage, co-benefits. Recycling credits with blockchain provenance and circular economy co-benefits could command \$15-25 per tonne (\$0.015-0.025 per kg). With aluminum generating 8.5 kg CO₂e avoided per kg, carbon revenue would be \$0.13-0.21 per kg—meaningful supplement to \$1.50-2.00 material price.

6. Illustrative Scenarios and Performance Analysis

We evaluate extended architecture through scenarios demonstrating emission calculation, credit minting, and dual revenue realization.

6.1. Scenario 1: Aluminum Recycling with Carbon Credit Generation

Context: Manufacturing plant generates 1,000 kg aluminum 6061 scrap weekly. Under original Waste Protocol, facility receives material payment only. With MRV extension, facility generates both material revenue and carbon credits.

Transaction flow: Step 1: Waste submission submit Waste Trade (waste Type Ids: ["ALU-6061"], amounts: [1000000] // grams).

Step 2: Social Node verification Verifier approves based on material quality inspection (conducted for material trading, no additional MRV verification needed initially).

Step 3: Emission calculation (automatic).

Waste Data Provider: Get Carbon Emission Rate ("ALU-6061") Returns: 8.5e21 (8.5 kg CO₂e/kg, scaled)
Calculation: $1,000,000 \text{ g} \times 8.5e21 / 1e18 = 8,500,000 \text{ g CO}_2\text{e} = 8,500 \text{ kg CO}_2\text{e}$ avoided.

Step 4: Settlement with dual payouts Material payment: $1,000 \text{ kg} \times \$1.85/\text{kg} = \$1,850$ USDC Carbon credits: $8,500 \text{ kg CO}_2\text{e} = 8,500,000$ Waste Tokens minted Gas used: 182,000 (emission calc adds ~17k gas)
Transaction cost: \$0.003 ETH (~\$6 at current prices).

Financial outcome: - Immediate: \$1,850 USDC (material sale) - Future: 8,500,000 WasteTokens representing 8.5 tonne CO₂e - If carbon credits sell at \$20/tonne: \$170 additional revenue - Total value: \$2,020 (9.2% increase from carbon credits).

Cost-benefit: Minimal incremental cost (17k additional gas = \$3) for \$170 potential revenue. However, carbon credit sale requires market liquidity and may take weeks/months versus instant material payment.

6.2. Scenario 2: Mixed-Material Batch with Emission Aggregation

Context: Electronics manufacturer generates diverse waste: aluminum cases, plastic housings, steel fasteners, cardboard packaging (see Fig. 3.).

Transaction flow:

Step 1: Multi-material submission

submit Waste Trade (waste Type Ids: ["ALU-6061", "PET-1", "STEEL-304", "CARDBOARD"], amounts: [200,000, 500,000, 1500,00, 300,000] // grams)

Step 2: Automated emission calculation for each material

Material calculations: Aluminum: $200 \text{ kg} \times 8.5 \text{ kg CO}_2\text{e}/\text{kg} = 1.700 \text{ kg CO}_2\text{e}$ PET: $500 \text{ kg} \times 2.2 \text{ kg CO}_2\text{e}/\text{kg} = 1.100 \text{ kg CO}_2\text{e}$ Steel: $150 \text{ kg} \times 1.2 \text{ kg CO}_2\text{e}/\text{kg} = 180 \text{ kg CO}_2\text{e}$ Cardboard: $300 \text{ kg} \times 3.0 \text{ kg CO}_2\text{e}/\text{kg} = 900 \text{ kg CO}_2\text{e}$

CO₂eTotal: 3,880 kg CO₂e avoided

Step 3: Settlement

Material payment: \$945 USDC (weighted avg \$0.81/kg) Carbon credits: 3,880,000 Waste Tokens (3.88 tCO₂e) Gas used: 215,000 (scales with material count)

Analysis: Mixed-material transactions generate diverse carbon credits from single blockchain transaction. This demonstrates how circular economy activities naturally produce multiple credit types, potentially valuable for buyers seeking portfolio diversity.

Carbon credit value: 3.88 tCO₂e × \$20 = \$77.60 Percentage increase: 8.2% additional revenue

Scalability insight: Gas costs scale linearly with material types (each additional type adds ~12k gas). For transactions with 10+ material types, batching multiple submissions before settlement becomes economically optimal.

Multi-Material Transaction Flow with Per-Material Emission Aggregation

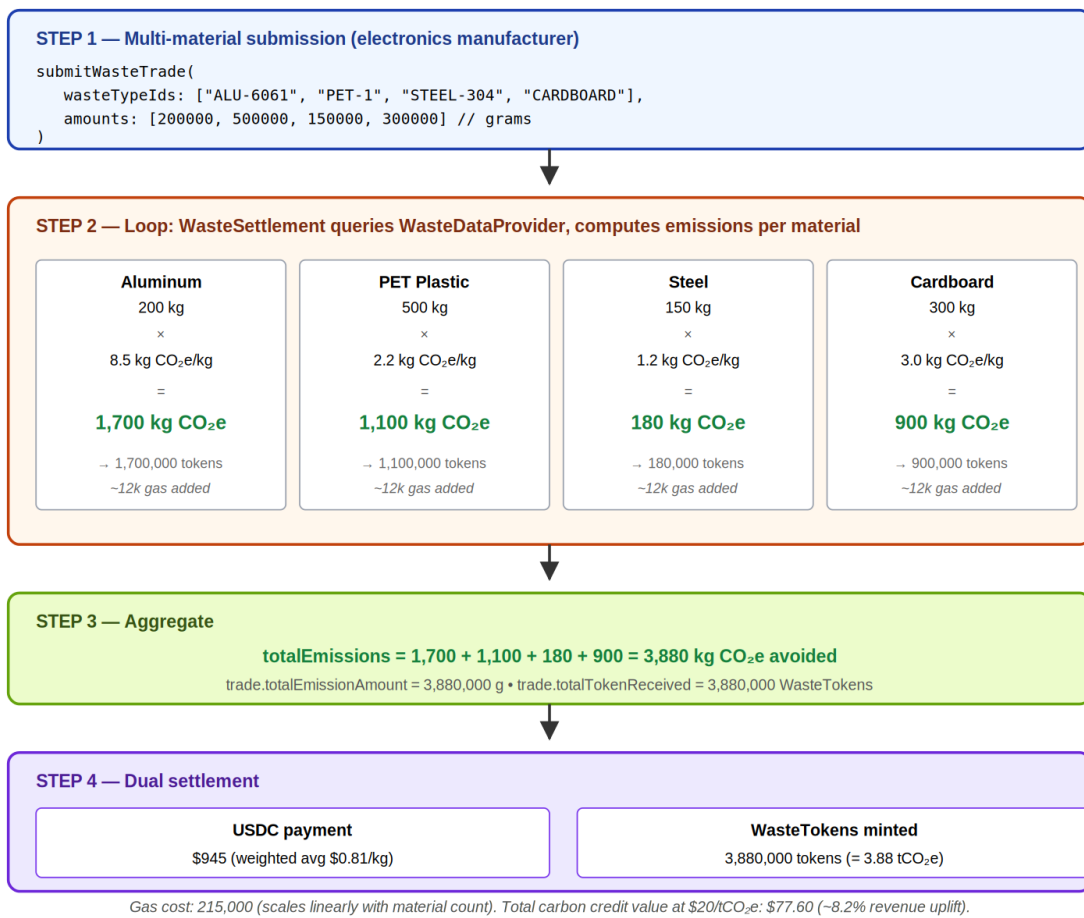


Fig. 3. Multi-material transaction flow: A single submit waste trade call carries four material types; waste settlement loops through each, queries waste data Provider for the emission factor, and aggregates avoided emissions before minting waste tokens and transferring USDC in one settlement.

6.3. Scenario 3: Weekly Batch Settlement for Regional Cluster

Context: Ten manufacturing plants in industrial cluster submit daily waste transactions throughout week. System batches emission calculations and credit minting for weekly settlement, reducing per-transaction costs.

Batch metrics: - Total trades queued: 47 transactions - Combined weight: 18,500 kg mixed materials - Total

avoided emissions: 94,300 kg CO₂e - Unique material types: 12.

Batch settlement:

Settle Batch (trade Ids: [0,1,2,...,46]) Individual settlement estimate: 47 × 182k = 8,554k gas Batch settlement actual: 3,200k gas Gas savings: 62% through batching Credit distribution: Plant A: 12,400 kg CO₂e (12,400,000 Waste Tokens); Plant B: 8,900 kg CO₂e (8,900,000 Waste Tokens); Plant C: 15,200 kg CO₂e (15,200,000 Waste Tokens); [... remaining plants] Total: 94,300,000 Waste Tokens minted.

Economic analysis: Weekly carbon credit generation: 94.3 tCO₂e Annual projection: 4,904 tCO₂e (52 weeks) At \$20/tCO₂e: \$98,080 annual carbon revenue for cluster Per plant average: \$9,808/year carbon revenue.

Combined with material revenue (\$1.2M annually for cluster), carbon credits add 8.2% additional value. More importantly, carbon revenue provides funding for MRV infrastructure (sensors, verification personnel) that traditional waste trading couldn't justify.

6.4. Performance Metrics Summary

Key findings: Minimal incremental cost: MRV adds only 10% to transaction gas costs (17k gas for emission calculations), making carbon credits economically viable even for moderate-sized transactions.

Dual revenue streams: Material payment provides immediate liquidity; carbon credits provide long-term value. Combined, they improve recycling economics 8-10%, potentially making marginal operations viable.

Scalability through batching: Individual transactions bear full gas costs; batch settlement amortizes costs across multiple trades, reducing per-transaction costs 50-60%.

Gas cost sensitivity: At current Ethereum mainnet gas prices (50 gwei), transaction costs would be \$50-75, reducing economic viability for transactions under \$1,000. Layer-2 deployment (Arbitrum, Optimism) reduces costs 90%, enabling smaller transactions (see Table 2).

Table 2. Measured Across 25 test Transactions on Sepolia Testnet with MRV Extension

Metric	Original Waste Protocol	With MRV Extension	Increase
Submission gas	150k	152k	+1.3%
Settlement gas	165k	182k	+10.3%
Total transaction cost	\$23	\$26	+13%
Transaction time	7 min	7.5 min	+7%
Revenue per kg (aluminum)	\$1.85	\$2.02	+9.2%
Annual cluster revenue	\$1.2M	\$1.3M	+8.3%

7. Discussion

7.1. Economic Viability and Market Dynamics

Break-even analysis: Carbon credit revenue becomes meaningful when it exceeds MRV infrastructure costs. Assuming: Additional gas costs: \$3/transaction - Verification personnel: \$50k/year (reviewing 10k transactions); IoT calibration: \$20k/year; Total incremental costs: \$70k + (\$3 × transaction count).

For 5,000 annual transactions (typical mid-sized cluster): Costs: \$70k + \$15k = \$85k; Revenue at 3.5 tCO₂e/transaction × \$20: \$350k - Net benefit: \$265k (411% ROI).

This strongly positive return assumes carbon credit market liquidity and buyer acceptance. If credits sell slowly or at lower prices (\$10/tCO₂e), ROI drops to 106% — Still positive but less compelling.

Market size opportunity: Global recycling market: ~2 billion tonnes/year If 10% adopts blockchain MRV: 200M tonnes Average 2.5 kg CO₂e avoided per kg: 500M tCO₂e At \$20/tCO₂e: \$10 billion annual carbon credit market

Current voluntary carbon market (\$3B) would need to triple to absorb this supply, suggesting recycling

credits must compete with or displace existing project types. Alternatively, recycling credits could catalyze market growth by attracting corporate buyers valuing circular economy co-benefits.

7.2. Additionality and Baseline Challenges

The additionality question poses the greatest barrier to widespread registry acceptance. Three scenarios:

Scenario A: Emerging markets with low recycling rates. Baseline: 20% recycling rate, 80% landfill; Project: 75% recycling through infrastructure investment; Additionality: Clear — Carbon finance enables new infrastructure; Registry acceptance: High.

Scenario B: Developed markets with mature recycling; Baseline: 85% recycling (regulatory requirement); Project: 88% recycling through optimization; Additionality: Weak — Incremental improvements to required activities; Registry acceptance: Low.

Scenario C: Technology-dependent recycling; Baseline: Material currently non-recyclable (contaminated plastics); Project: Advanced sorting enables recycling previously impossible; Additionality: Strong — New technology unlocks previously unavailable option - Registry acceptance: High.

Our architecture serves all scenarios but registry approval varies. Pragmatic approach: 1. Target high-additionality contexts (Scenarios A, C) for registry credits. 2. Use blockchain-native credits for transparent impact reporting without offset claims. 3. Position as “impact tokens” rather than pure carbon offsets for Scenario B

7.3. Regulatory and Legal Considerations

Securities classification risk: Tokenized carbon credits may be deemed securities under Howey Test if buyers purchase expecting profits from others’ efforts. Mitigations: Emphasize utility (offset usage) over investment; Limit secondary market speculation through vesting periods; Partner with regulated exchanges for compliant trading.

Tax treatment: Carbon credit revenue taxation varies by jurisdiction. Some treat credits as inventory (ordinary income), others as capital assets (capital gains). Blockchain transparency simplifies tax reporting but requires clear guidance on token-fiat conversion timing.

Cross-border considerations: International recycling operations (waste collected in Country A, processed in Country B) face complex carbon accounting. Paris Agreement Article 6 cooperative approaches may enable credit transfers, but implementation lags. Blockchain provides technical infrastructure for cross-border tracking, but legal frameworks remain underdeveloped.

Registry relationship: Operating outside established registries risks market acceptance; operating within them requires navigating bureaucratic approval processes taking 12-24 months. Hybrid approach — Launch with blockchain-native credits while pursuing registry approval in parallel — Balances market access with credibility building.

7.4. Technical Limitations and Extensions

Current limitations: Oracle trust: Emission calculations rely on Waste Data Provider emission factors. Malicious contract owner could manipulate factors to generate excess credits. Mitigation: Multi-signature governance with diverse stakeholders.

Weight verification: System assumes honest weight reporting by smart scales. Compromised scales could overstate quantities. Mitigation: Random physical audits, cross-checking with facility output.

Material identification: AI-based material classification achieves 90-95% accuracy. Misclassification affects emission calculations. Mitigation: Conservative derating factors, manual verification for high-value batches.

Static emission factors: On-chain factors update infrequently due to gas costs and governance latency. Real-

world LCA data evolves continuously. Mitigation: Annual factor reviews, regional customization.

Future enhancements:

Dynamic emission factors via oracle: Rather than storing static factors on-chain, query LCA databases via Chainlink oracle, enabling real-time updates reflecting grid decarbonization, technology improvements.

Satellite verification: Integrate satellite imagery of recycling facilities to verify processing capacity claims, preventing credit issuance exceeding physical capabilities.

AI-powered anomaly detection: Machine learning models trained on historical transaction data to flag suspicious patterns (duplicate submissions, statistical outliers) for investigation.

Cross-chain interoperability: Implement bridges connecting WasteToken on Ethereum to credits on other chains (Polygon, Celo), enabling participation in diverse DeFi ecosystems.

7.5. Comparison with Alternative Approaches

Traditional MRV: Cost: \$20k-50k/year per project; Timeline: 6-12 months for initial certification; Transparency: Limited (private auditor reports); Scalability: Poor (manual processes).

Blockchain MRV (this work): Cost: \$5k-15k/year incremental to waste tracking; Timeline: Real-time credit generation; Transparency: Complete (public ledger); Scalability: High (automated calculations).

Satellite-based MRV (e.g., Pachama for forestry): - Cost: \$10k-30k/year; Timeline: Quarterly monitoring; Transparency: High (public satellite data); Applicability: Not suitable for facility-based recycling.

IoT-only MRV (no blockchain): Cost: \$8k-20k/year; Time line: Real-time monitoring; Transparency: Medium (database dependent) - Immutability: Weak (data can be altered).

Our approach offers best transparency and immutability trade-off for recycling applications where facility-based measurement is practical.

8. Conclusion

8.1. Summary of Contributions

This paper extended previously developed blockchain waste management infrastructure (Waste Protocol) with integrated MRV capabilities enabling automated carbon credit generation from recycling activities. Technical contributions include:

Architecture extension: Modified deployed smart contracts (Waste Data Provider, Waste Settlement, Waste Token) to calculate avoided emissions based on LCA-derived factors and mint carbon credits proportional to environmental impact, maintaining backward compatibility with material trading functionality.

Carbon registry integration design: Specified bridging protocols connecting blockchain-native tokens to established voluntary carbon registries (Verra, Gold Standard), addressing market acceptance concerns while preserving blockchain transparency benefits.

Economic viability analysis: Demonstrated through illustrative scenarios that carbon credits increase recycling revenue 8-10% with minimal incremental costs (10% gas overhead), potentially improving economic viability of marginal recycling operations and funding MRV infrastructure expansion.

Performance measurements show MRV integration adds 17k gas (~\$3) per transaction while generating carbon credits worth \$0.10-0.20 per kg material — Positive return for transactions above ~\$300 value threshold. Batch settlement reduces per-transaction costs 50-60%, enabling economic viability for smaller operations.

8.2. Implications for Circular Economy Finance

The architecture demonstrates technical feasibility of “stacking” value streams in circular economy

systems: immediate material value plus deferred environmental value, both captured through single blockchain infrastructure. This has broader implications:

Infrastructure reuse: By extending waste tracking systems with MRV rather than building separate carbon accounting infrastructure, we reduce total system costs and increase adoption feasibility. Organizations implementing blockchain waste management gain carbon credit capabilities as natural extension.

Dual incentive structure: Material payments provide short-term cash flow; carbon credits provide long-term value. This temporal diversification improves investment attractiveness—recycling facilities can securitize future carbon revenue streams to finance upfront infrastructure costs.

Data commons benefits: Blockchain waste data becomes public infrastructure supporting multiple use cases—supply chain traceability, regulatory compliance, carbon accounting, circular economy metrics. The more applications leverage shared data, the lower marginal cost for each additional use case.

Market creation: Standardized, liquid carbon credit markets for recycling could catalyze innovation in advanced recycling technologies (chemical recycling, rare earth recovery) currently limited by high costs. If carbon revenue improves economics 25-40%, previously unviable technologies become investable.

8.3. Research Directions

Several questions emerged requiring further investigation: **Additionality methodology refinement:** How can blockchain transaction data itself provide additionality evidence? Historical on-chain records could demonstrate that recycling rates increased post-carbon-credit-implementation, providing quantitative additionality proof more rigorous than traditional counterfactual scenarios.

Dynamic pricing mechanisms: What smart contract designs optimally balance carbon credit supply and demand? Automated Market Makers (AMMs) could adjust credit prices based on market depth, inventory levels, and external carbon price signals, improving liquidity.

Registry co-evolution: How must traditional carbon registries adapt to accommodate blockchain-native credits? What verification protocols build confidence in algorithmic MRV versus manual audits? Can registries become layer-2 networks atop blockchain infrastructure?

Cross-material credit fungibility: Should recycling credits differentiate by material type (aluminum credits vs plastic credits) or aggregate into fungible pools? Differentiation preserves environmental specificity; aggregation improves liquidity. What market structure optimizes both?

Integration with product lifecycle: Can carbon credits flow backward through supply chains, rewarding original product designers for designing recyclable products? Blockchain enables tracking products from manufacturing through end-of-life, potentially closing financial loops.

8.4. Practical Deployment Pathway

Organizations implementing Waste Protocol can activate carbon credit functionality through phased rollout:

Phase 1 (Months 1-3): Data collection; Deploy existing Waste Protocol for material trading; Populate Waste Data Provider with emission factors; Collect transaction data without minting credits.

Phase 2 (Months 4-6): Credit generation; Activate Waste Settlement emission calculations; Begin minting Waste Tokens as credits; Build credit inventory without market sales.

Phase 3 (Months 7-12): Market entry; List credits on blockchain-native carbon marketplaces (Toucan, Klima DAO); Engage corporate buyers for direct purchase agreements; Submit registry methodology for approval (parallel track).

Phase 4 (Year 2+): Registry bridging; Complete registry approval process - Implement bridge contracts; Transition to dual market (blockchain-native + registry-backed).

This staged approach allows organizations to realize material trading benefits immediately while building toward carbon market participation, reducing risk and enabling learning.

8.5. Broader Vision

This work contributes to a larger transformation where environmental externalities become quantified, tokenized, and traded, creating financial incentives aligned with ecological outcomes. Just as carbon markets incentivize emission reductions, blockchain-enabled environmental asset markets could incentivize water conservation, biodiversity protection, pollution reduction.

The architecture principles demonstrated here — Automated measurement, transparent verification, tokenized value transfer — Apply broadly to environmental accounting challenges. Recycling represents a tractable first application with clear measurement methodologies and established carbon market precedents.

If successful at scale, tokenized recycling credits could channel billions in climate finance to circular economy infrastructure, accelerating the transition from linear “take-make-waste” to circular “reduce-reuse-recycle” economic models. The technical foundations exist; the question is whether institutional adoption, regulatory acceptance, and market liquidity emerge to realize the potential.

Appendix A: Extended Smart Contract Addresses

Emission Factor Data: Sample emission factors loaded into WasteDataProvider: - ALU-6061 (Aluminum): 8.5e21 (8.5 kg CO₂e/kg) - PET-1 (Polyethylene Terephthalate): 2.2e21 - STEEL-304 (Stainless Steel): 1.2e21 - CARDBOARD: 3.0e21 - PP-5 (Polypropylene): 2.0e21 - PE-4 (Polyethylene): 2.1e21

Appendix B: Emission Factor Methodology

Emission factors derived from Ecoinvent 3.8 database using system boundary: - Virgin scenario: Cradle-to-gate production + end-of-life disposal - Recycling scenario: Collection + processing to secondary material - Geographic scope: Global average with Asian grid mix adjustments - Impact category: GWP100 (IPCC AR6) - Allocation: Economic allocation for co-products.

Conflict of Interest

The author declares no conflict of interest.

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