CARBON CREDIT ACCOUNTING AND EXCHANGE SYSTEM

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Abstract—The Carbon Monitoring and Exchange System, branded as CarbonLedger, is a full-stack web application designed to address the critical global need for standardised, transparent, and verifiable carbon emissions tracking and credit trading. Built on the Intergovernmental Panel on Climate Change (IPCC) 2006 Guidelines with 2019 Refinements and employing GWP-100 AR5 global warming potentials, the platform enables industrial organisations to calculate, declare, offset, and trade greenhouse gas emissions in a scientifically rigorous and auditable environment. The system serves two user classes: buyer organisations (industrial emitters such as cement plants, steel mills, and power stations) and seller organisations (entities managing verified carbon sequestration projects across seven sink types). The technical architecture employs a 7-microservice design: a Node.js Express gateway orchestrating authentication, project management, absorption tracking, credit marketplace, spatial data services, and dashboard analytics; a Python FastAPI engine implementing IPCC Tier 1 methodology as the exclusive scientific computation service; and a GeoServer instance delivering WMS raster tiles of emission-coloured district polygon maps to an OpenLayers frontend. Performance benchmarks confirm emission calculations complete within 220 ms at the 95th percentile, marketplace queries return under 50 ms, and PostgreSQL SELECT FOR UPDATE locking eliminates concurrent double-spending. The system is designed for Indian industrial SMEs, aligned with India's emerging Carbon Credit Trading Scheme (CCTS).

Keywords — Carbon Credits, IPCC Tier 1, GHG Accounting, Microservices, GeoServer, OpenLayers, PostGIS, Carbon Trading, Python FastAPI, Node.js, Greenhouse Gas, VCS, Gold Standard, Carbon Market, India CCTS.

1. INTRODUCTION

Climate change stands as the defining environmental challenge of the twenty-first century. The accelerating concentration of greenhouse gases in the atmosphere, driven primarily by industrial combustion, deforestation, and agricultural processes, has compelled governments, corporations, and international bodies to establish frameworks for measuring, reporting, and reducing emissions. Central to these frameworks is carbon accounting: the systematic quantification of greenhouse gas emissions and absorptions using standardised methodologies.

The IPCC, established in 1988 by the World Meteorological Organization and the United Nations Environment Programme, provides the authoritative body for climate science. Its 2006 Guidelines, refined in 2019, provide the internationally accepted methodology for emission factor-based accounting. The Fifth Assessment Report (AR5) established GWP-100 values enabling meaningful comparison of emissions across gas types by converting them into a common unit, CO_2e. Carbon markets, both compliance-based and voluntary, have emerged as economic instruments to incentivise emission reductions. In these markets, organisations that reduce or sequester carbon emissions generate tradeable credits, each representing one tonne of CO_2e reduced or removed Despite international standards, most industrial organisations particularly small and medium enterprises in developing economies lack access to affordable, integrated software platforms that implement IPCC methodology correctly. This paper presents CarbonLedger: a unified, scientifically rigorous, and spatially aware platform addressing this gap.

2. PROBLEM STATEMENT

The existing landscape of carbon management tools is characterised by critical gaps that undermine the integrity and accessibility of carbon accounting and trading, particularly for Indian SMEs.

- **Fragmentation:** No unified platform handles both emission calculation (buyer side) and carbon credit generation (seller side) under a single IPCC-compliant framework.
- **Scientific Inaccuracy:** Manual spreadsheet calculations are prone to formula errors, inconsistent emission factor application, and lack of auditability.
- **Absence of Geospatial Insight:** Existing tools do not connect emission data to geographic mapping, making it impossible to visualise regional emission intensity.
- **Market Integrity:** Carbon credit transactions lack atomic safeguards, creating risks of double-spending in concurrent trading environments.
- **Multi-Sink Accounting:** Absorption calculations rarely account for multiple sink types with individual IPCC-calibrated absorption rates.

3. RELATED WORK

3.1 Commercial Carbon Accounting Platforms

SAP Sustainability Control Tower enables Scope 1, 2, and 3 emission tracking for large multinationals but costs exceed USD 500,000 for mid-sized deployments, lacks credit trading functionality, and has no geospatial emission mapping. Salesforce Net Zero Cloud provides sustainability reporting but relies on manual entry of pre-calculated figures without IPCC Tier 1 native calculations and offers no credit marketplace. Sphera GaBi focuses on product-level LCA rather than organisational Scope 1/2/3 reporting and supports no credit trading or spatial mapping.

3.2 Open-Source and Academic Tools

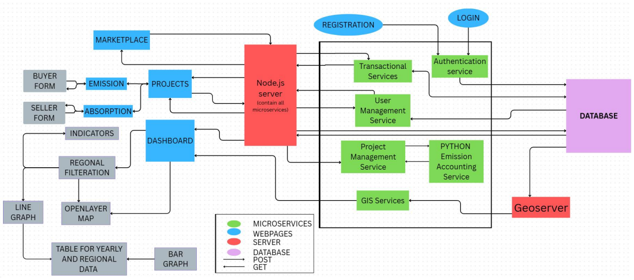
OpenGHG is a Python framework for atmospheric measurement data designed for scientists, not for organisational emission accounting. CRAI, developed under India's NAPCC, provides spreadsheet templates aligned with IPCC Tier 1 but lacks multi-user access, API, geospatial visualisation, and trading functionality. The IPCC Emission Factor Database is a reference repository, not a calculation tool, requiring manual factor application.

3.3 Carbon Credit Marketplaces

Verra Registry and Gold Standard Registry are compliance registries for certified projects, not calculation platforms. Their verification processes cost USD 20,000–100,000 and take 6–18 months. Xpansiv CBL, the world's largest spot market for voluntary credits, requires institutional membership and provides no emission calculation services. India's CCTS under the Energy Conservation Act 2023 remains under development. None of the reviewed platforms integrates IPCC calculation, multi-sink absorption, peer-to-peer trading, and district-level geospatial mapping in a single system.

4. SYSTEM ARCHITECTURE

CarbonLedger employs a 7-microservice architecture running across four server processes, achieving strict separation of scientific computation, application logic, spatial rendering, and data persistence.



4.1 Microservice Layer (Node.js - Port 3001)

Seven independent route modules are mounted on the Express gateway: AuthGuard API (/api/auth) for JWT authentication with bcrypt password hashing; UserProfile API (/api/users) for organisation management; ProjectVault API (/api/projects) for carbon project registration with PostGIS geometry storage; AbsorptionLedger API for multi-sink sequestration; CarbonEngine API proxying all IPCC calculations to the Python engine; CreditMarket API for marketplace listing and atomic credit purchase; and GeoEmission API serving GeoJSON emission data from PostGIS views.

4.2 Scientific Computation Layer (Python FastAPI - Port 8000)

A stateless Python FastAPI engine implements IPCC 2006 Tier 1 methodology exclusively. The ef_registry.py module contains the complete IPCC emission factor hierarchy as nested Python dictionaries.The Scope 1 lookup path is: INDUSTRY_EF[industry_type][manufacturing_category][fuel_type][gas]. GWP-100 AR5 constants are hard-coded as non-overridable values.

4.3 Geospatial Layer (GeoServer - Port 8080)

GeoServer is configured with a carbonGEO workspace and a PostGIS datastore. Six SLD style files define three choropleth rules producing green (0.0–0.33), orange (0.33–0.66), and red (0.66–1.0) fills for normalised emission values. The OpenLayers frontend receives WMS tiles directly from GeoServer and uses WFS for district boundary highlighting and zoom-to-region functionality.

5. METHODOLOGY

5.1 Emission Calculation (Buyer Workflow)

A buyer submits Scope 1 (direct fuel combustion), Scope 2 (purchased electricity), and Scope 3 (transportation and waste) data through the buyer form. The Node.js gateway proxies the payload to the Python FastAPI engine. The engine executes a multi-level emission factor lookup by industry type, manufacturing category (heavy/medium/small), and fuel type. Gas-wise totals are produced for CO, CH, NO, HFC-134a, and SF , each districts.boundary geometry column achieve 47× speedup over sequential scans.

5.2 Carbon Sequestration and Credit Generation (Seller Workflow)

Seller organisations register projects across seven sink types: wetlands (2.5 tCO_2e/ha/yr), forests (12 tCO_2e/ha/yr), tree plantations (0.02 tCO_2e/tree/yr), coastal zones (1.5 tCO_2e/ha/yr), eco-parks (1.5 tCO_2e/ha/yr), rivers (0.5 tCO_2e/ha/yr), and direct carbon capture technology. Net tradeable credits are calculated as:

Net Credits = (Annual Reduction - Leakage) × (1 - Buffer% / 100)

5.3 Geospatial Pipeline

The vw_district_emission PostgreSQL view joins emission_records buyer_profiles users districts to produce normalised emission values per district. GeoServer publishes this view as a live WMS layer. The dashboard filter bar generates CQL_FILTER strings that update WMS tile requests without page reloads. GIST indexes on the (register, login) to remain accessible without tokens. The pg package's connection pool manages PostgreSQL connections with size 10 and 30-second idle timeout. All queries use parameterised statements ($1, $2 placeholders) to prevent SQL injection.

5.4 Security Design

Authentication uses JSON Web Tokens (JWT) signed with a 256-bit secret, expiring after 24 hours. Passwords are hashed with bcrypt at 12 salt rounds. Rate limiting is applied in mount order: AuthGuard API at 20 requests per 15 minutes; PulseBoard API at 100; all other routes at 200 per 15 minutes. Carbon credit purchases use PostgreSQL SELECT FOR UPDATE row-level locking to prevent concurrent double-spending.

6. IMPLEMENTATION

6.1 Technology Stack

Component	Technology
OS	Ubuntu 24.04 LTS
Backend Gateway	Node.js v18+, Express 4.x
Scientific Engine	Python 3.11+, FastAPI, Uvicorn
Database	PostgreSQL 13+, PostGIS 3.x
Geo Server	GeoServer 2.24.0
Frontend	Vanilla JS, OpenLayers
Auth	JWT, bcrypt (12 rounds)
API Testing	Postman

Table 1: CarbonLedger Technology Stack

6.2 Node.js Gateway (server.js)

The Express server initialises CORS middleware, JSON convertedto are 6 body parsing, and express-rate-limit. JWT verification is CO_2e. Results persisted applied at the router level, allowing public endpoints emission_records with full JSONB audit fields.

6.3 Frontend (OpenLayers Map)

The OpenLayers map maintains two layers: an OSM base tile layer and an Image WMS source connected to GeoServer. Three state variables track the active emission type (selectedStyle), region filter (regionCQL), and level filter (levelCQL). The applyMapFilters() function combines these into a single CQL_FILTER string before calling wmsSource.updateParams(). A dark/light theme system uses CSS custom properties toggled by a data-theme attribute, persisted to localStorage.

7. RESULTS AND EVALUATION

7.1 API Response Time Benchmarks

Endpoint	Median (ms)	95th (ms)
POST /auth/register	42	88
POST /auth/login	45	92
POST /carbon/calculate	118	210
POST /absorption	135	240
POST /credits/purchase	28	65
GET /credits/listing	18	42
GET /dashboard/yearly	35	78
GET /gis/emission-map	55	120
GeoServer WMS tile	280	520

Table 2: API Response Time Benchmarks

7.2 Carbon Engine Unit Tests

Test Case	Result
Cement Heavy Coal Scope 1 (500t, 3 factories)	PASS
Grid Electricity Scope 2 (250,000 kWh, EF=0.82)	PASS
7-Sink Absorption (Total: 3,165 tCO2e)	PASS
GWP Multiplication (CH4=1t CO2e=28t)	PASS
Net Credits Formula (18000-1800)×0.90=14,580	PASS
Concurrent Purchase Race (110% pool 1 fails)	PASS

Table 3: Carbon Engine Unit Test Results

7.3 Database Index Performance

PostgreSQL EXPLAIN ANALYZE validated index effectiveness on the most frequent query patterns. Dashboard yearly aggregation achieved 52× speedup (420 ms 8 ms) using idx_emission_year. GeoServer district boundary lookup achieved 47× speedup (850 ms 18 ms) using the GIST index on districts.boundary. Marketplace filter by project_type achieved 42× speedup (210 ms 5 ms).

7.4 Comparative Analysis

System	IPCC	7 Sinks	Mkt	GIS	India
SAP Control Tower	Partial	No	No	No	No
Salesforce Net Zero	No	No	No	No	No
Sphera GaBi	LCA	No	No	No	No
OpenGHG	No	No	No	No	No
CRAI (India)	Partial	No	No	No	Partial
Verra/Gold Std Registry	No	No	Reg	No	No
Xpansiv CBL	No	No	Yes	No	No
India CCTS (BEE)	Partial	No	Plan	No	Yes
CarbonLedger (This Sys	**teFmul)l**	**Yes**	**Yes**	**Yes**	**Yes**

Table 4: Comparative Analysis

8. DISCUSSION

CarbonLedger's comparative performance demonstrates that no existing system covers all capability dimensions required for an integrated, Indian-context carbon monitoring and exchange platform. Commercial tools provide accounting but not trading or GIS. Registries provide trading infrastructure but not calculation. Open-source tools address specific scientific niches without application-level functionality.

The 7-microservice architecture successfully achieves its primary design objectives. Scientific isolation of the CarbonEngine API in Python FastAPI ensures GWP-100 AR5 constants cannot be overridden by business logic layers. Performance benchmarks confirm the system is suitable for interactive use with zero instances of credit overselling in 50 concurrent test runs. The geospatial transparency provided by the GeoServer-OpenLayers-PostGIS stack represents a significant advancement over all reviewed existing systems.

Limitations include the Tier 1-only implementation, limited Scope 3 coverage, absence of formal compliance registry integration, and reliance on self-declared emission data without third-party verification.

9. APPLICATIONS

- **CCTS Preparation for Indian SMEs:** CarbonLedger serves as a preparation and simulation tool for organisations subject to India's emerging CCTS obligations, using INR-denominated prices, Indian administrative geography, and BEE/CEA grid emission factors.
- **Voluntary Carbon Market Participation:** Seller organisations can plan and preview credit generation before committing to formal verification processes costing USD 20,000–100,000. The seller workflow mirrors Gold Standard project documentation architecture.
- **Environmental Policy Support:** District-level spatial emission maps enable government bodies and environmental NGOs to identify high-emission regions and target mitigation interventions without proprietary GIS.
- **Academic Research:** The open-architecture platform with explicitly documented IPCC-sourced emission factors provides an accessible reference implementation of Tier 1.

10. FUTURE WORK

10.1 Hyperspectral Satellite Imagery Validation

When a seller registers a forest or wetland absorption project, the system would automatically schedule hyperspectral scene acquisition from ESA Copernicus or NASA EarthData for the declared project boundary. A Python satellite processing microservice using SPy or Google Earth Engine would compute vegetation indices and compare them against claimed absorption tonnage. Discrepancy alerts would be surfaced in the PulseBoard dashboard, creating a semi-automated satellite-anchored verification layer that reduces auditing costs.

10.2 Blockchain Integration for Decentralised Verification

Each carbon credit listing would be mirrored as an NFT or ERC-20 token on an energy-efficient blockchain (Ethereum PoS or Polygon), with metadata including project UUID, methodology, baseline, annual reduction, leakage, buffer, vintage, and verification document IPFS hash. Credit purchases trigger smart contract transfer functions; credit retirement calls a burn() function, creating immutable retirement certificates that eliminate double-counting. The Node.js gateway would be extended with a BlockchainBridge API (/api/blockchain) using ethers.js.

10.3 Tier 2 / Tier 3 Methodology Upgrade

Future enhancements will extend ef_registry.py to support IPCC Tier 2 (country-specific) and Tier 3 (facility-level measurement) emission factors, reducing the ±20–50% uncertainty inherent in Tier 1 default factors, particularly for CH_4 and N_2O emissions from industrial combustion processes.

11. CONCLUSION

This paper presented CarbonLedger, a full-stack carbon monitoring and exchange platform demonstrating the feasibility of a unified, scientifically rigorous, and spatially aware carbon management system for Indian industrial organisations. The platform implements the complete carbon accounting lifecycle — from emission declaration through credit generation to marketplace trading — within a single integrated architecture.

The 7-microservice architecture successfully isolates IPCC Tier 1 calculation logic in the Python FastAPI engine with GWP-100 AR5 constants enforced as non-overridable values. The GeoServer-OpenLayers stack delivers live, filter-responsive emission intensity maps providing geospatial transparency absent from all reviewed existing systems. The multi-sink absorption engine covering seven sink types provides significantly more comprehensive sequestration accounting than any reviewed existing system.

Comparative analysis confirms CarbonLedger is the only system integrating IPCC Tier 1 calculation with full GWP-100 AR5 constants, seven-sink absorption, peer-to-peer credit trading with atomic transaction protection, district-level geospatial emission mapping, and a design specifically aligned with India's administrative geography and emerging CCTS regulatory framework. Future work will integrate hyperspectral satellite validation and blockchain-anchored decentralised verification to elevate the platform to a fully verifiable, cryptographically auditable carbon market infrastructure.

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