ATHLAS VERITY

Carbon Dioxide Removal Calculation Methodology

Mass-Balance, Lifecycle & AI-Verified Durable Removal Quantification

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Reference Standards: [('puro-earth', 'Puro.earth (2023). CO2 Removal Certificate (CORC) methodology - durable CDR.'), ('iso-14064-2', 'ISO 14064-2:2019. Quantification, monitoring and reporting of GHG removals.'), ('iso-14067', 'ISO 14067:2018. Carbon footprint of products (LCA basis).'), ('verra-vcs', 'Verra VCS v4.3. Program-level crediting rules and permanence requirements.'), ('ipcc-2006', 'IPCC (2006). 2006 Guidelines - AFOLU & Industrial Processes Volumes.'), ('iea-ccus', 'IEA CCUS protocols - capture, utilization and storage accounting.'), ('quantified-durability', 'Approved durability/declining-storage models for 100-yr permanence.'), ('iso-14064-3', 'ISO 14064-3:2019. Specification for verification of GHG statements.')]
Status: RELEASED — COMPLIANCE
Engine: Carbon Dioxide Removal (CDR) Verifier Engine · **Project:** Athlas Verity Carbon Verification Engine

1. Purpose & Scope

This document establishes the standardized, fully transparent mechanism for quantifying the durable carbon dioxide removal (tonnes CO2e) from engineered and novel CDR technologies verified by Athlas Verity — including direct air capture (DAC), biochar, mineralisation and other permanent pathways. It applies rigorous mass-balance and lifecycle accounting into a single auditable pipeline.

It aligns with Puro.earth CORC, ISO 14064-2/14067 and Verra permanence requirements, and is prepared for compliance, verification, reporting and carbon-standard publication.

Scope — Forest Project Types

- **Direct Air Capture (DAC)** — Engineered capture of atmospheric CO2 with durable storage
- **Biochar** — Pyrolysed biomass with long-lived carbon in soil/application
- **Mineralisation** — Weathering/mineral carbonation of CO2 into stable minerals
- **Enhanced weathering / novel** — Emerging permanent removal pathways with verified durability

Aligned Standards

- **Puro.earth CORC** — CO2 Removal Certificate methodology for durable CDR
- **ISO 14064-2:2019** — Quantification, monitoring and reporting of GHG removals
- **ISO 14067:2018** — Carbon footprint of products (LCA basis)
- **Verra VCS v4.3** — Program-level crediting rules and permanence requirements
- **IEA CCUS protocols** — Capture, utilization and storage accounting

2. Data Acquisition (Process & Storage)

CDR crediting is process- and monitoring-dominated rather than satellite-dominated, but the engine integrates process metering, mass-flow, storage telemetry and, where applicable, satellite/remote verification (e.g. biochar land application, mineral storage site monitoring). The table defines the operational data stack.

Sensor	Type	Retrieved Variables	Resolution / Revisit	Temporal Coverage	Role in Pipeline
Process mass-flow meters	On-site metering	Capture rate (tCO_2/unit time), capture efficiency, storage feed	Continuous	Live / period	Primary capture accounting
Storage telemetry	Monitoring network	Injected/stored CO_2, reservoir pressure & integrity, leakage detection	Interval	Live	Storage permanence & containment verification
LCA inventory	ISO 14067 inventory	Embodied energy, feedstock, supply-chain emissions (tCO_2e per unit)	Lifecycle vintage	Per assessment	Net removal basis (gross - LCA)
Durability / decay model	Approved declining-storage model	Storage fraction vs time, 100-yr permanence factor	Model vintage	Per pathway	Durability classification & reversal risk
Energy / feedstocks metering	On-site + invoices	Electricity, heat, feedstock quantity (boundary)	Interval / monthly	Live	Attribution of LCA emissions
Satellite / remote (biochar, storage site)	Sentinel-2 / InSAR	Land application extent, storage site surface deformation/leakage	10-30 m	Periodic	Independent verification & site monitoring

3. Dataset Inventory

Dataset / Product	Source	Resolution	Frequency
Capture mass flow (tCO2)	On-site process meter	Continuous	Live / monthly
Storage / injection telemetry	Monitoring network	Interval	Live
LCA inventory (tCO2e)	ISO 14067 assessment	Lifecycle vintage	Per assessment
Energy & feedstock inputs	On-site + invoices	Boundary-defined	Monthly
Durability / decline factor	Approved decay model	Pathway-specific	Per assessment
Storage-site monitoring	Reservoir / InSAR / satellite	10-30 m / interval	Periodic
Biochar application extent	Sentinel-2 + records	10 m	Annual / per campaign
Measurement drift / calibration	Meter QC logs	Interval	Annual
Chain-of-custody records	Serialization system	Unit-level	Per unit
Independent audit files	Third-party verifier	Batch	Per vintage

Preprocessing note: All data are bound to a defined project boundary and reconciled across meters and invoices. Mass flows are drift-checked with ML and cross-validated; LCA and durability factors are fixed at approved vintages; unit-level chain-of-custody is serialized for full traceability.

4. AI Engine Architecture (Process Data → Net Removal → Credit)

The Carbon Dioxide Removal (CDR) Verifier Engine is a process-and-storage-to-credit inference pipeline. Each stage is deterministic, logged, and reproducible from raw inputs to final credits.

1. **Data Ingestion & Boundary**
   Ingest metering, mass flow, storage telemetry and LCA within a defined project boundary; timestamp & unit normalization.
2. **Mass-Balance Reconciliation**
   ML reconciles capture, storage and losses; detects measurement drift in flow streams.
3. **Net Removal Computation**
   net = gross_captured - LCA_emissions (energy, feedstock, supply chain); bound to net atmospheric drawdown.
4. **Durability Classification**
   Assign permanence class (100-yr+) and declining-storage factor per approved model.
5. **Reversal / Leakage Monitoring**
   Storage-site telemetry + InSAR/satellite detect reversal events; discount or buffer where required.
6. **Uncertainty Quantification**
   Quantile / Monte Carlo (N=1000) propagate mass-balance, LCA and durability-decline uncertainty.
7. **Calibration & Bias Correction**
   Residual correction vs independent audit / third-party verification before any unit is issued.
8. **Chain-of-Custody Serialization**
   Serialize each net removal unit with a unique provenance chain (capture batch → storage → vintage).
9. **Additionally & Eligibility**
   Confirm the removal occurs only because of the project and meets permanence/eligibility bar.
10. **On-chain Issuance**
    netVerifiedRemovalTCO2e units minted on-chain under AURA consensus with vintage and serial.

5. Machine-Learning Models

The AI engine is a stacked ensemble. Cross-model disagreement is treated as a source of uncertainty, not ignored. Models are trained on process telemetry and validated against independent audits.

Model	Input	Validation	Rationale / Output
Random Forest (RF)	Tabular process features (flow, temp, pressure, feed); quantile variant for P10/P50/P90	Held-out process periods; RMSE / R2 / bias	Robust net-removal estimate & anomaly baseline
XGBoost	Non-linear interactions among process & LCA features	Independent periods vs audit; RMSE / R2	Handles interactions; strong tabular baseline
Deep Autoencoder (Drift)	Reconstruction of expected mass-flow sequences; flags meter drift	ROC/AUC on labeled drift events	Detects capture/storage measurement anomalies
Ensemble Stacker	Outputs of RF, XGBoost, drift model as meta-features; ridge/GBM meta-model	Ensemble spread tracked as uncertainty budget	Final consensus estimate; spread → uncertainty margin

Training & Calibration Blocks

1. Target definition: net captured/removed tCO$_2$e from reconciled mass balance.
2. Temporal & batch-separated folds; strict no-leakage validation split.
3. Quantile regression forests + MC dropout for calibrated P10/P50/P90 intervals.
4. Validation metrics: RMSE, R2, bias, and 95% interval coverage vs independent audit.
5. Empirical residual calibration on third-party verification data before inference.
6. Periodic re-calibration as new LCA vintages and monitoring data arrive.

> **Integrity safeguard:** spatially separate folds prevent geographic leakage; held-out field plots independently validate every prediction before any credit is issued.

6. Step-by-Step Calculation Procedure

1 Process Mass-Balance

Capture gross tCO_2 from process metering; reconcile storage and losses.

2 Lifecycle Assessment

Compute LCA emissions (energy/feedstock/supply chain) from ISO 14067 inventory.

3 Net Removal

net_removal = gross_captured - LCA_emissions (net atmospheric drawdown).

4 Durability Classification

Assign permanence class and storage-decline factor (100-yr horizon).

5 Reversal / Leakage Risk

Apply storage monitoring + InSAR/satellite; discount or buffer for reversal risk.

6 Uncertainty & Conservatism

Monte Carlo (N=1000) on mass-balance, LCA, durability; credit = CI-95% lower bound.

7 Chain-of-Custody

Serialize each unit (capture batch → storage → vintage) with provenance hash.

8 Independent Audit & Verification

Third-party verification confirms net removal and storage permanence.

9 On-chain Issuance

netVerifiedRemovalTCO2e units minted under AURA consensus.

7. Uncertainty & Conservatism

The engine reinforces structural conservatism with Monte Carlo simulation (N = 1000). Mass-balance, LCA and durability-decline uncertainty are drawn from distributions defined by their mean and standard deviation. The crediting boundary is the lower bound of the 95% confidence interval.

```
uncertainty_margin = max(deterministic_net - lower_crediting_bound, 0)
```

```
net_verified = deterministic_net - uncertainty_margin
```

Each calculation carries an equation trace linking every input to final output, so auditors can reproduce every figure. Durability and reversal risk are covered by a monitoring schedule and, where required, a buffer. Issuance never exceeds the CI-95% lower bound — consistent with honest permanence accounting.

8. Numerical Example (End-to-End, Pixel to Credit)

Inputs (500 ha restoration, conservative):

- **Technology:** Direct Air Capture (DAC) facility with permanent geological storage
- **Gross captured:** 10,000 tCO_2 (process metered)
- **LCA emissions:** 1,500 tCO_2e (energy + feedstock + supply chain)
- **Durability factor:** 95% (100-yr permanence, approved declining-storage model)
- **Uncertainty:** measurement uncertainty 3%
- **Boundary:** Net atmospheric drawdown, chain-of-custody serialized

Stage	Calculation	Result
Net Removal (gross - LCA)	`10,000 - 1,500 = 8,500 tCO2e`	**8,500 tCO2e**
Durability Adjustment	`8,500 × 0.95 = 8,075 tCO2e`	**8,075 tCO2e**
Conservatism (CI-95%)	`8,075 × (1 - 0.03) ≈ 7,833 tCO2e`	**7,833 tCO2e**
Final verified units	`Monte-Carlo floor, lower bound`	**7,833 units**

> **Conclusion:** Of 10,000 tCO_2 gross capture, only ~78% passes to 7,833 net durable removal units after lifecycle, durability and conservatism — reflecting honest, permanent CDR accounting.

9. Verification & On-chain Lifetime

1. The netVerifiedRemovalTCO2e units are serialized (AV-CDR001-{serial}) and written to the Athlas Verity registry with provenance linking each capture batch, LCA vintage and storage site.
2. AURA consensus re-checks the mass-balance and permanence bounds; every removal unit is traceable to its source process data and independent audit.
3. On retirement, the credit certificate is minted and the serial is burned on-chain, preventing double claiming of the same durable removal.

10. Regulatory & Compliance Framework

This section defines the compliance pathway through which AV-CDR001 credits are rendered eligible, additional, monitored, and independently verifiable under recognised carbon standards. It formalises the audit requirements referenced throughout this methodology.

A. Eligibility & Applicability

Project eligibility. A project is eligible for AV-CDR001 crediting only where it demonstrably falls within the applicable scope of this methodology and the governing standards: **Puro.earth CORC · ISO 14064-2:2019 · ISO 14067:2018 · Verra VCS v4.3 · IEA CCUS protocols**.

- **Boundary & commencement:** a defined project boundary, a documented start date, and enforceable legal right to the carbon rights being claimed.
- **Land/asset status:** verifiable baseline land-use or asset status at commencement, with no prior registry registration of the same credits (no double counting).
- **Additionally screen:** the activity must not be required by law, regulation, or business-as-usual practice.

B. Additionality Assessment

Additionally is established using a documented, evidence-based procedure consistent with the governing registry (Verra VCS, CDM, ISO 14064-2, or Puro.earth as applicable). The assessment applies a sequential test:

1. **Legal/regulatory test** — confirm no statutory obligation to undertake the activity.
2. **Investment/financial test** — demonstrate the activity is not clearly the most economically attractive course absent carbon revenue (economic analysis against a conservative financial benchmark).
3. **Barrier test** — identify material financial, technological, institutional, or capacity barriers that the carbon revenue overcomes.
4. **Common-practice test** — confirm the activity type is not widespread within the relevant region/asset class.

All assumptions, data, and model outputs supporting the additionality determination are retained in the audit trail for independent review.

C. Monitoring, QA/QC & Sampling Plan

Monitoring plan. A written monitoring plan defines indicators, measurement frequency, instrumentation, and data-retention rules for every crediting interval. All raw inputs (satellite scenes, field records, meter logs, mass-flow data) are time-stamped, georeferenced where applicable, and retained in the auditable registry.

Sampling design. Ground-truth and field sampling follow a stratified random design with documented sample size determined by a target confidence/precision budget, giving statistically valid estimates and defensible uncertainty bounds.

QA/QC. Quality-assurance/quality-control procedures include: duplicate and independent re-measurement checks, instrument calibration traceability, outlier screening, and reconciliation against independent data sources. Any data gap or anomaly is logged and conservatively treated.

D. Third-Party Verification & Audit Trail

Independent verification. Issuance is conditioned on independent desk review and, where required, field or on-site verification by a qualified verifier. The verifier re-checks input provenance, calculation logic, uncertainty treatment, and conservatism settings against this methodology.

Audit trail. Every issued unit carries a unique serial (AV-CDR001-[SERIAL]), a provenance hash of all input datasets and model runs, and an immutable on-chain record. On retirement the serial is burned, preventing double counting and enabling independent audit at any time.

Re-verification cycle. Monitoring reports, calculations, and verifier findings are re-assessed at each crediting interval; buffer and risk parameters are re-evaluated against observed disturbance events before further issuance.

E. Permanence, Leakage & Buffer

Permanence & reversal risk. Carbon-dioxide-removal permanence is storage-medium dependent. Geological storage is assessed for containment integrity over the monitoring horizon; biogenic/material storage is subject to a non-permanence risk (**NPR**) assessment and buffer withholding. Reversal monitoring uses storage-integrity and re-release indicators, with buffer drawdown on verified loss.

Leakage. Upstream emissions and displacement (energy inputs, land competition) are included in the system boundary and netted from net removals to prevent crediting of non-additional or shifted emissions.

F. SDG Contribution & Safeguards

SDG contribution. Activities are evaluated against SDG 13 (Climate Action), SDG 9 (Industry, Innovation and Infrastructure) and SDG 7. **Safeguards.** Environmental and community safeguards cover storage-site safety, water use, and land competition; projects document country-of-origin oversight.

11. References

ID	Reference
`puro-earth`	Puro.earth (2023). CO2 Removal Certificate (CORC) methodology - durable CDR.
`iso-14064-2`	ISO 14064-2:2019. Quantification, monitoring and reporting of GHG removals.
`iso-14067`	ISO 14067:2018. Carbon footprint of products (LCA basis).
`verra-vcs`	Verra VCS v4.3. Program-level crediting rules and permanence requirements.
`ipcc-2006`	IPCC (2006). 2006 Guidelines - AFOLU & Industrial Processes Volumes.
`iea-ccus`	IEA CCUS protocols - capture, utilization and storage accounting.
`quantified-durability`	Approved durability/declining-storage models for 100-yr permanence.
`iso-14064-3`	ISO 14064-3:2019. Specification for verification of GHG statements.

12. Key Glossary

Term	Definition
DAC	Direct Air Capture - engineered removal of CO_2 from ambient air.
LCA	Lifecycle Assessment - cradle-to-grave emissions accounting.
Net removal	Gross captured CO_2 minus lifecycle and process emissions.
Durability / permanence	Duration of storage; CDR requires 100-yr+ horizon.
Declining-storage model	Approved decay curve of stored carbon over time.
Mass balance	Reconciliation of captured, stored and lost CO_2 flows.
Chain of custody	Serialized provenance from capture batch to storage to credit.
P10 / P50 / P90	10th/50th/90th percentile of the estimation distribution.
CORC	CO_2 Removal Certificate (Puro.earth).
AURA consensus	Athlas Verity on-chain verification & provenance protocol.
tCO2e	Tonnes of carbon dioxide equivalent - unit of removal unit.
Buffer	Reserve covering reversal / permanence risk.
ISO 14067	Standard for product carbon footprint (LCA).
MRV	Measurement, Reporting and Verification.

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13. Trademark & Non-Affiliation Disclaimer

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14. Supplementary Notes

14.1 Purpose and Status of This Document

This methodology is provided as an informative, professional reference describing the technical design and calculation approach of the Athlas Verity carbon-verification engine. It is intended to support understanding, compliance readiness, verification, and reporting by project proponents, verifiers, and standard bodies.

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This document reflects the actual process metering, storage-telemetry, and LCA implementation of the Athlas Verity Carbon Dioxide Removal (CDR) Verifier Engine and is prepared as a reference for compliance, verification, reporting, and carbon standard publication.