# NEXERO

*Carbon Capture & Storage Solutions*

# CCS Chain Optimizer

## An AI-Enabled Operations & Assurance Layer for $CO_2$ Transport & Storage Networks

*White Paper — Version 1.3 (Expanded & Referenced)*

Geographic Scope: UK & Europe First | Scalable to the Middle East

Date: 19 December 2025

Classification: Confidential

Owner: David Donovan | Nexero Ltd. | david.donovan@nex-ero.com

Prepared for: CCS Transport & Storage Operators, Cluster Consortia, Industrial Emitters, Regulators, and Investors

## DISCLAIMER

This document is provided for informational and strategic purposes only and does not constitute legal, regulatory, financial, or investment advice. All regulatory frameworks, market arrangements, and policy signals referenced herein are subject to change. Prospective investors, partners, and operators are advised to seek independent professional counsel and to verify all technical, commercial, and compliance requirements with the relevant competent authorities and counterparties prior to engagement.

All references cited within this white paper are drawn from publicly available sources accessed on or before 19 December 2025. NEXERO makes no representation or warranty regarding the completeness, accuracy, or continued applicability of third-party sources. Readers should independently verify all material claims before relying upon them for decision-making purposes.

## Abstract

As carbon capture and storage (CCS) transitions from isolated, project-level deployments to integrated, multi-user transport and storage (T&S) networks across the United Kingdom and continental Europe, the operational and governance challenges facing network operators evolve fundamentally. The shift from constructing individual infrastructure assets to orchestrating shared capacity across multiple industrial emitters, under concurrent nomination demands, binding capacity constraints, and intensified regulatory verification expectations, necessitates a purpose-built digital operating layer that does not yet exist at scale in the market.

This white paper presents the CCS Chain Optimizer: a modular, AI-enabled platform designed to serve as the digital operations and assurance interface for shared $CO_2$ T&S networks. The platform integrates four core functional capabilities: (i) probabilistic forecasting and feasibility assessment; (ii) structured nomination and renomination workflow management; (iii) transparent constraint identification, allocation, and rescheduling; and (iv) assurance-grade traceability through data provenance, immutable audit trails, and MRV-ready evidence packs.

The CCS Chain Optimizer is architecturally aligned with the governance obligations articulated in the UK CCS Network Code (DESNZ, 2023, 2025), which mandates transparent constraint communication and allocation mechanisms, and with the enforcement posture established by Ofgem's $CO_2$ Transport and Storage guidelines (Ofgem, 2024). In parallel, EU policy direction—including the Net-Zero Industry Act's target of at least 50 million tonnes per annum of injection capacity by 2030 and the European Commission's 2025 public consultation on $CO_2$ markets and infrastructure (European Commission, 2025)—reinforces the strategic imperative for interoperable, configurable digital operations platforms.

The recommended entry point, or minimum viable product (MVP), is the productisation of the daily nominations and constraint allocation workflow. This represents the highest-frequency operational pain point across shared T&S networks and provides an immediate, measurable value proposition through utilisation uplift and curtailment reduction, while simultaneously establishing the foundational data backbone required for subsequent MRV automation and, where commercially pertinent, certificate-grade storage documentation.

## Table of Contents

## 1. Executive Summary

Carbon capture and storage in the United Kingdom and Europe is undergoing a structural transition. Having progressed through the feasibility and early demonstration phases, the sector is now converging upon shared, multi-user $CO_2$ transport and storage networks in which multiple industrial capture installations compete for finite pipeline, terminal, and injection capacity. This operational model is fundamentally analogous to that of regulated utility networks: it demands structured nomination processes, equitable and transparent capacity allocation under constraint, and a comprehensive evidentiary record capable of withstanding regulatory scrutiny, commercial dispute, and third-party verification.

The CCS Chain Optimizer is a proposed AI-enabled operations and assurance platform designed to occupy this critical interface. Architecturally, the platform sits above existing operational technology (e.g., SCADA systems and process historians) and commercial systems (entitlements registers, contracts), and provides a unified digital layer for: forecasting and feasibility validation; nomination and renomination workflow orchestration; constraint detection, transparent allocation, and rescheduling; and the generation of traceable, audit-ready evidence packs for monitoring, reporting, and verification (MRV).

The platform's governance design is aligned to the obligations and expectations articulated in the UK CCS Network Code, which anticipates capacity constraints and requires the transport and storage company to publish relevant constraint information and to notify affected users, with transparent allocation mechanisms deployed to manage such constraints (DESNZ, 2023, 2025). Ofgem's published enforcement guidance for $CO_2$ T&S further underscores that operational controls and auditability are non-discretionary elements of regulated network operation (Ofgem, 2024). In parallel, EU policy instruments—including the Net-Zero Industry Act and the European Commission's October 2025 consultation on $CO_2$ markets and infrastructure—signal the progressive formalisation of cross-border T&S market rules and interoperability standards (European Commission, 2025).

The strategic entry point for the CCS Chain Optimizer is the MVP productisation of the daily nominations and constraint allocation workflow. This module addresses the highest-frequency operational pain point across shared networks and delivers immediate, quantifiable value through utilisation uplift and curtailment reduction while concurrently establishing the data infrastructure required for downstream MRV automation and certificate-grade documentation.

## 2. The Scaling Problem: Operational & Assurance Challenges in Shared CCS Networks

Shared CCS transport and storage networks present a qualitatively distinct operational challenge from single-asset or bilateral CCS projects. The critical transition is from engineering and commissioning a discrete facility to continuously operating a networked system in which multiple parties submit competing demands into finite capacity, and in which the evidentiary trail must be sufficiently comprehensive, traceable, and defensible to satisfy regulators, auditors, counterparties, and, increasingly, carbon market verifiers.

### 2.1 Sources of Operational Complexity

The complexity inherent in shared CCS networks can be disaggregated into five principal domains, each of which introduces distinct challenges to network operations and assurance:

- **Capture Variability.** Industrial capture installations are subject to planned and unplanned outages, ramp-rate limitations, variable capture efficiency, and fluctuations in $CO_2$ quality and impurity composition. These variations directly affect the volume and specification of $CO_2$ presented to the transport network, requiring dynamic forecasting and real-time feasibility assessment.
- **Transport Variability.** Pipeline and compressor infrastructure operates within defined operating envelopes that are themselves subject to planned maintenance, equipment availability, and seasonal or operational constraints. Terminal capacity and inventory levels further introduce scheduling dependencies that must be resolved in advance of physical delivery.
- **Storage Variability.** Geological injection sites are subject to well-level availability constraints, downtime for maintenance or integrity surveillance, and operating envelope restrictions that may change in response to reservoir monitoring data. These constraints are often less predictable than transport-side limitations and may emerge on short notice.
- **Commercial Variability.** Multiple shippers or users hold differentiated entitlements, capacity products, and contractual priorities. Reconciling these commercial positions with physical network realities requires structured nomination, allocation, and settlement processes that are transparent, auditable, and aligned to agreed rules.
- **Verification Variability.** MRV expectations are evolving rapidly, driven by EU CCS Directive monitoring obligations (EUR-Lex, 2018), emerging carbon market integrity frameworks, and buyer-side due diligence requirements. The documentation burden placed on T&S operators by these expectations is material and growing.

### 2.2 What Is at Stake

The consequences of inadequate operational coordination and assurance in shared CCS networks are significant across operational, commercial, and reputational dimensions:

- **Lost abatement and revenue** resulting from avoidable curtailment or under-utilisation of transport and storage capacity.

- **Elevated operating costs** attributable to inefficient recovery from disruptions, manual coordination overhead, and reactive rather than anticipatory constraint management.
- **Heightened dispute risk** in the absence of transparent allocation rules, auditable decision records, and structured notice and communication processes.
- **Escalating verification costs** as evidence packs become increasingly bespoke, labour-intensive, and time-consuming to produce without a systematic data backbone.
- **Erosion of investor and stakeholder confidence** if storage integrity documentation and chain-of-custody records are perceived as insufficiently credible or repeatable.

**Design Principle — Human-in-the-Loop Governance:** A fundamental design constraint of the CCS Chain Optimizer is that CCS T&S operations are safety- and compliance-sensitive. The platform therefore enforces a human-in-the-loop governance model: all recommendations are AI-assisted, but operational decisions require explicit approvals, explainability, and auditable records prior to execution.

# 3. UK and European Market Context and Regulatory Signals

## 3.1 United Kingdom: Network Code Obligations and Digital Operating Requirements

The UK CCS Network Code establishes the primary governance framework for access to and operation of $CO_2$ transport and storage networks. The Code anticipates capacity constraints as a foreseeable operational condition and specifies that the transport and storage company is required to publish relevant constraint information and to notify affected users in a timely and transparent manner. Allocation mechanisms are to be applied consistently and with documented rule precedence (DESNZ, 2023, 2025).

In practical terms, these obligations translate into a requirement for systems capable of managing entitlements, forecasting intake, processing nominations, computing allocations, and issuing notices at operational scale and with consistent auditability. Ofgem's published enforcement guidelines and penalty policy for $CO_2$ T&S further reinforce that this is not a best-effort regulatory environment: operational controls, record retention, and decision auditability are integral components of compliant network operation (Ofgem, 2024). Any digital operating layer deployed in this context must therefore be designed not only to deliver operational outcomes but also to evidence compliance behaviours—including process controls, decision rationales, and audit-grade record retention.

## 3.2 European Union: Scale Targets and Cross-Border Infrastructure

The European Union is actively constructing the enabling policy and infrastructure conditions for scaled CCS deployment. The Net-Zero Industry Act articulates a target of at least 50 million tonnes per annum of $CO_2$ injection capacity by 2030, representing a substantial step-change in the scale of geological storage activity across the continent (European Commission, n.d.). Cross-border $CO_2$ transport infrastructure projects are recognised within the Trans-European Networks for Energy (TEN-E) framework and may qualify as Projects of Common Interest or Projects of Mutual Interest, with corresponding access to Connecting Europe Facility funding instruments (European Commission, n.d.).

In October 2025, the European Commission launched a public consultation on $CO_2$ markets and infrastructure, with a formal legislative or regulatory initiative anticipated in 2026 (European Commission, 2025). This consultation signals that the market rules governing third-party access, interoperability standards, and quality specifications for $CO_2$ T&S services will continue to evolve. The implication for platform developers is clear: any digital operating solution must be architecturally configurable, capable of adapting to evolving regulatory and commercial frameworks without requiring fundamental system redesign.

## 3.3 MRV and Environmental Integrity: EU CCS Directive Monitoring Requirements

The EU CCS Directive (Directive 2009/31/EC, as consolidated) establishes the overarching legal framework for the environmentally safe geological storage of $CO_2$, including detailed monitoring obligations defined with reference to a site-specific monitoring plan approved by the relevant competent authority (EUR-Lex, 2018). These obligations impose requirements for systematic monitoring plan mapping to operational data streams, rigorous data provenance and quality controls, and audit-ready reporting and record retention throughout the lifetime of a storage site.

For shared T&S network operators, these requirements create a material documentation burden that extends beyond individual site-level compliance and into the operational and commercial workflows governing $CO_2$ delivery and injection. The CCS Chain Optimizer is designed to address this burden through embedded assurance-by-design principles, discussed further in Section 5.

### 3.4 Industry Benchmarking: Emerging Digital CCS Workflows

Digital workflow development within the CCS sector is already visible in the market, providing useful benchmarks and signals regarding the trajectory of the industry. Northern Lights, Europe's first operational $CO_2$ storage facility, issued its first $CO_2$ storage certificates in December 2025, with documentation quantifying stored volumes and providing a lifecycle emissions breakdown associated with transport and operations (Northern Lights, 2025). Northern Lights has also entered into a strategic collaboration with SLB and Microsoft to develop digital CCS workflows and an open-source, Azure-compliant data platform (SLB, 2023; Northern Lights, 2023). These developments collectively indicate that the convergence of digital operations capability and verifiable documentation is becoming a core infrastructure requirement for scalable T&S services.

# 4. Platform Definition: What the CCS Chain Optimizer Delivers

## 4.1 Conceptual Positioning

The CCS Chain Optimizer is a modular, purpose-built platform that occupies the operational-commercial interface of a shared CCS transport and storage network. It is explicitly not an operational technology system: it does not replace SCADA, process control, or instrumentation. Rather, it functions as the 'network operating system' layer that codifies and enforces network rules (entitlements, nomination cycles, allocation logic); integrates measured and operational state data from upstream systems; supports optimisation and rapid rescheduling under constraint; and produces an auditable, traceable record of all decisions, submissions, and evidence packs required for assurance.

## 4.2 Minimum Viable Outcomes — Day One Capabilities

The platform is designed to deliver the following minimum outcomes from initial deployment:

- Provision of a single, authoritative source of truth for user entitlements and delivery points, specifying who holds the right to deliver or inject $CO_2$, at which connection points, and under which registered capacity products.
- Acceptance, validation, and processing of forecast submissions and daily nominations against entitlements and declared operational constraints, with systematic rejection and notification for submissions that fall outside acceptable parameters.
- Detection and management of capacity constraints; transparent computation of allocations in accordance with pre-defined and configurable rule sets; timely issuance of constraint notices; and triggering of renomination workflows.
- Maintenance of immutable audit logs encompassing all submissions, calculations, approvals, notices, and changes to master data, sufficient to support regulatory audit, commercial dispute resolution, and internal governance review.
- Publication of operator-facing and user-facing reporting dashboards covering nominations versus actuals, network utilisation, constraint events, allocation outputs, deviations, and trend analytics.

## 4.3 Primary Users and Decision Points

The platform is architected around the specific decision-making accountabilities that characterise shared T&S network operations:

- **Control Room / Operations:** Accept or reject nominations; declare constraint events; approve rescheduling plans; manage constraint event lifecycle.
- **Commercial / Market Operations:** Maintain entitlements and capacity product registries; approve allocation rule sets; oversee settlement artefacts and reconciliation outputs.
- **Users / Shippers:** Submit forecasts and nominations within defined cut-off windows; acknowledge constraint notices; submit renominations; monitor allocation and delivered volume status.

- **Assurance / Compliance:** Confirm evidence pack completeness; map monitoring plan requirements to data checks; manage audit response workflows and verification interactions.

## 4.4 Functional Modules

The platform is organised into six integrated functional modules, each with defined inputs, outputs, and governance artefacts:

| Module | Key Inputs | Key Outputs | Governance Artefacts |
|---|---|---|---|
| **Capacity &** Entitlements Register | Users, delivery points, registered capacity, capacity products, constraint rules | Entitlements snapshots, capacity reporting, allocation baselines | Versioning, approvals, change logs |
| **Forecasts &** Nominations | Multi-horizon forecast submissions, daily nominations, cut-off schedules, validation rules | Accepted nominations, deviations, nomination packs | Submission records, acceptance/rejection rationale |
| **Constraint Mgmt &** Allocation | Asset availability, capacity envelopes, constraint windows, allocation rules | Constraint notices, pro-rata allocations, surplus reallocation recommendations | Constraint log, allocation calculations, notices archive |
| **Optimisation &** Scenario Engine | Forecast distributions, constraints, objectives, safety/operability limits | Feasible schedules, recovery plans, scenario rankings | Scenario basis, sensitivity logs, decision record |
| **Evidence Engine** (MRV-Ready) | Metered volumes, custody transfer records, injection records, monitoring-plan mapping | Evidence packs, reconciliations, exception reports | Provenance links, audit trails, verification pack |
| **Integration &** Governance | APIs, historian extracts, file drops, master data, quality rules | Validated datasets, canonical model outputs, alerts | Lineage, data quality KPIs, immutable audit entries |

*Table 1: CCS Chain Optimizer — Functional Module Summary*

## 4.5 Operational Success Criteria

The platform is considered operationally successful when the following conditions are consistently met:

- Operators are able to produce a validated nomination and allocation pack within defined cut-off windows, including during active constraint events, without manual intervention or spreadsheet-based workarounds.
- Users receive timely, consistent, and complete constraint notices and are able to submit renominations through structured, governed workflows.

- Allocated volumes, delivered volumes, and injected volumes can be reconciled end-to-end with traceable, auditable calculations linking each stage of the chain.
- Evidence packs can be generated on demand—for regulatory audits, governance reviews, dispute resolution, or customer documentation—with complete provenance and quality-state tagging.

# 5. AI & Optimisation: Capabilities, Boundaries, and Governance

## 5.1 The Boundary Between Measurement and Inference

A foundational principle of the CCS Chain Optimizer's design is the explicit and auditable separation between measured, derived, and inferred data. AI does not replace calibrated instrumentation. Measured values originate from custody transfer meters, pressure and temperature sensors, composition analysers, injection metering systems, and operational status logs maintained by upstream operational technology. AI capabilities are applied specifically where they add demonstrable control-room value: prediction, anomaly detection, and decision support under conditions of uncertainty.

The platform explicitly tags every data record with a provenance label indicating whether the value is (a) measured—sourced directly from an approved instrument or system; (b) derived—produced through documented engineering conversions or aggregations; or (c) estimated or inferred—generated through gap-filling, forecasting, or scenario modelling. Each record further carries model version information (where applicable) and a quality-state indicator, ensuring that auditors and operators can unambiguously distinguish between factual and estimated values at every stage of the decision chain.

## 5.2 Core AI and Analytical Functions

The AI and analytics layer of the CCS Chain Optimizer comprises four principal functions:

- **Probabilistic Forecasting.** Multi-horizon probabilistic forecasts are generated for capture availability, effective transport capacity, and injection availability, drawing on historical operational data, planned maintenance schedules, and seasonal patterns. Forecast outputs include confidence intervals and scenario sensitivities rather than single-point estimates, enabling operators to make informed decisions under uncertainty.
- **Anomaly Detection.** The platform provides early warning capabilities for meter drift, missing or delayed data, implausible readings, and deviations between nominated and delivered volumes. Anomaly signals are surfaced to operators with contextual information and severity indicators to support rapid investigation and response.
- **Recommendation Generation.** Optimisation-driven schedules and allocation recommendations are produced through a hybrid approach combining constraint-based optimisation with ML-driven heuristics. All recommendations are accompanied by feasibility proofs, rationale highlighting binding constraints and trade-offs, uncertainty indicators, and auditable approval workflows.
- **Assurance Automation.** The Evidence Engine employs reconciliation logic and document intelligence to map monitoring plan requirements to data checks, enabling fast, complete, and consistent evidence pack generation with full provenance traceability.

## 5.3 Optimisation as the Primary Value Engine

A significant proportion of the high-impact decisions within shared CCS networks are best addressed through constraint-based optimisation rather than through pure machine learning approaches. The allocation of constrained capacity, the generation of feasible schedules, and the recovery from unplanned disruptions while simultaneously respecting safety limits, operating envelopes, and contractual obligations are fundamentally structured optimisation problems. AI enhances optimisation performance through improved input forecasts and uncertainty quantification and can accelerate computational throughput through warm-start techniques and learned heuristics; however, the governance logic governing allocation and scheduling decisions remains explicit, configurable, and auditable.

### 5.4 Model Governance and Reproducibility

In regulated, safety-sensitive, and commercially material CCS environments, analytical performance must be matched by governance rigour. The CCS Chain Optimizer adopts a hybrid decision framework in which measurement remains grounded in calibrated instrumentation and approved operational systems; machine learning supports probabilistic forecasting and anomaly detection; and operational decisions are computed via constraint-based optimisation subject to explicit rules, operating envelopes, and safety limits.

Model governance controls within the platform include: (a) version-controlled model artefacts and configuration; (b) documented training data lineage and feature set specification; (c) continuous performance monitoring and drift detection; (d) formal change control and approval processes for any deployment to production; and (e) retention of the full decision artefact set—comprising inputs, constraints, objective functions, solver outputs, and approvals—sufficient to reproduce outcomes for audit and dispute resolution purposes. Where forecast uncertainty materially affects allocation or rescheduling outcomes, the platform publishes confidence intervals and scenario sensitivity analyses rather than single-point recommendations.

Allocation fairness is treated as a governance construct rather than an opaque model output. Baseline allocation mechanisms (e.g., pro-rata allocation across registered capacities) are implemented as explicit, independently testable rules aligned to the relevant market framework, with any advanced allocation products represented through transparent configuration and documented rule precedence (DESNZ, 2023, 2025).

## 6. Data Architecture: Sources, Governance, and Provenance

### 6.1 Data Sources Across the CCS Value Chain

The CCS Chain Optimizer integrates data from across the full carbon capture and storage value chain. Representative data sources by domain include:

- **Capture:** Delivered $CO_2$ mass flow at custody transfer points, pressure and temperature measurements, $CO_2$ quality and impurity flags, plant availability states, and planned outage schedules.
- **Transport:** SCADA and historian summaries (flow and pressure), compressor status, pipeline operating envelopes, terminal capacity and inventory levels, and maintenance plans.
- **Storage:** Injection metering data, well and manifold availability constraints, downtime plans, operating envelopes, and surveillance and integrity event logs.
- **Commercial / Governance:** Entitlements and capacity products, nomination cycles and cut-off schedules, allocation rules, and the notices and communications archive.

### 6.2 Data Ingestion and Validation

Integration maturity across the early-stage CCS market varies materially between operators. The CCS Chain Optimizer is designed to support staged ingestion that evolves with operator readiness: secure file drops and scheduled extracts for pilot-stage deployments; structured APIs and event feeds for operational scaling. Regardless of the integration method employed, a consistent and rigorous validation framework is applied: completeness checks, range and plausibility validation, time alignment, duplicate detection, and cross-system reconciliation.

### 6.3 Canonical Data Model and Provenance

The establishment of a canonical data model is essential to avoid the proliferation of inconsistent, uncontrolled data representations—the 'spreadsheet sprawl' that characterises pre-digital operational environments. The canonical model standardises entities—users, delivery points, entitlements, nominations, constraints, allocations, and actuals—and preserves comprehensive provenance metadata for each record: source system, transformation steps applied, timestamp, and responsible party. This design enables traceable reconciliation and repeatable evidence pack generation across the full operational lifecycle.

### 6.4 Data Governance and Auditability

The data governance framework of the CCS Chain Optimizer encompasses:

- Defined data owners and stewards per operational domain—commercial, operations, storage, and assurance—with clear accountability for data quality and completeness.
- Immutable audit logs for all changes to entitlements, nominations, allocations, and evidence packs, providing an unbroken trail of actions and decisions.
- Data quality key performance indicators—covering completeness, timeliness, consistency, and reconciliation status—with exception workflows for systematic identification and resolution of data quality issues.

- Retention policies calibrated to regulatory audit expectations and contractual dispute resolution windows, ensuring that records are available for the full period required by the applicable governance framework.

# 7. MVP and Pilot Design for UK/Europe

## 7.1 Strategic Rationale: Nominations and Constraints as the Beachhead

The daily nominations and constraint allocation workflow represents the most pragmatic and commercially compelling entry point for the CCS Chain Optimizer. It is the highest-frequency operational process within a shared T&S network, is directly linked to revenue and abatement outcomes, and is a governance-critical activity under the UK CCS Network Code. Productising this workflow provides a controlled environment to establish the data provenance, audit trail, and user adoption foundations that underpin the subsequent deployment of MRV automation and certificate-grade assurance capabilities.

## 7.2 MVP Scope (v1)

The v1 MVP comprises the following functional scope:

- Capacity and entitlements register: users, delivery points, registered capacity, capacity products, and allocation rules.
- Forecast intake and validation across multiple planning horizons.
- Daily nomination and renomination workflow with defined cut-offs, validation logic, and approval gates.
- Constraint workflow: event capture, baseline pro-rata allocation computation, notice generation and archiving, and renomination triggering.
- Dashboards and export capability: nominations versus actuals, utilisation, constraint events, allocations, deviations, and audit logs.

## 7.3 Minimum Viable Data for a Pilot

The minimum dataset required to support a meaningful pilot is as follows:

- Per user/delivery point: delivered $CO_2$ mass flow time series and basic availability status.
- Transport and storage network: available capacity or capacity proxies; planned outage schedules; key asset availability states.
- Storage: injection availability constraints by period and planned downtime schedules.
- Commercial and governance: entitlements, nomination cycles and cut-off definitions, and constraint allocation rules.

## 7.4 Indicative Pilot Timeline (8–12 Weeks)

| Phase | Activities |
|---|---|
| Weeks 1–2 | Discovery: network topology mapping, rules capture, data source assessment, success metrics baselining, security and access provisioning. |
| Weeks 3–6 | Configuration: workflow setup, validation and allocation rule implementation, dataset ingestion, dashboard and audit log establishment. |

| | |
|---|---|
| Weeks 7–10 | Shadow operations: parallel processing against live or historical data, rule and analytics tuning, user training, output validation. |
| Weeks 11–12 | Acceptance: formal acceptance testing, handover pack preparation, and v2 scale plan development. |

*Table 2: Indicative Pilot Timeline*

### 7.5 Pilot Acceptance Evidence

Pilot acceptance is demonstrated when the following evidence criteria are satisfied:

- A complete end-to-end nomination cycle has been demonstrated, encompassing controlled submissions, systematic validations, and operator approvals.
- At least one simulated and one real (or historical) constraint event has been processed through the platform, producing transparent allocation outputs and notices with full audit trail.
- A reconciliation report has been generated showing nominations versus metered deliveries and injection (where available), with traceable calculations.
- An audit log export has been produced demonstrating who changed what and when, including all approvals, rejections, and notices.
- User training has been completed and an operational playbook for recurring cycles has been delivered and validated.

# 8. Architecture, Security, and Deployment

## 8.1 Security Design Requirements

CCS operational data is commercially sensitive and may have implications for physical safety. The CCS Chain Optimizer is designed to support regulated operations through a security posture that encompasses:

- Role-based access control (RBAC) with least-privilege defaults, ensuring that users access only the data and functions required for their defined operational role.
- Segregation of duties between operations, commercial, and assurance functions, preventing unauthorised combinations of access.
- Encryption in transit and at rest across all data flows and storage, with secure key management practices aligned to industry standards.
- Immutable audit logging for all operational actions and data modifications, with tamper-evident record integrity.
- Controlled data sharing to users: the platform publishes what is required under the relevant rules while protecting commercially sensitive information.

## 8.2 Deployment Options

The platform is designed to accommodate the diverse data residency, network segmentation, and operational preferences of T&S operators:

- **Cloud (UK/EU region):** Rapid deployment with scalable compute for optimisation and analytics workloads. Suitable for operators with mature cloud adoption and appropriate data classification frameworks.
- **Hybrid:** Sensitive operational and commercial data remains on-premise while the portal, workflow, and optimisation engine operate in a controlled cloud environment. Provides a pragmatic balance between deployment speed and data residency assurance.
- **On-premise:** Fully on-premise deployment for environments with strict data residency or network segmentation requirements.

## 8.3 Interoperability and Configurability

Given the expectation that market rules will continue to evolve as the UK CCS Network Code matures and EU cross-border frameworks are formalised, the platform treats allocation rules, nomination cycles, reporting templates, and notice formats as configurable policy artefacts rather than hard-coded system logic (DESNZ, 2023, 2025). This architectural decision enables operators to adapt the platform to evolving regulatory and commercial requirements without disruptive system redesign or extended development cycles.

# 9. Value Case and Success Metrics

Value realisation through the CCS Chain Optimizer is driven by four primary mechanisms: improved network utilisation, reduced avoidable curtailment, reduced coordination and verification overhead, and lower dispute risk through transparent and auditable decision processes.

## 9.1 Pilot Success Metrics

The following metrics are recommended for tracking value delivery during and following the pilot phase:

| Metric | Description |
| --- | --- |
| Utilisation Uplift | Delivered and stored $CO_2$ volumes versus baseline, measured overall and during active constraint periods. |
| Curtailment Reduction | Frequency and duration of curtailment events, relative to baseline, attributable to earlier constraint detection and improved rescheduling. |
| Decision Cycle Time | Elapsed time from constraint detection to issued allocation notice and revised nominations. |
| Dispute Indicators | Number of contested allocations and time-to-resolution, supported by audit trail evidence. |
| Evidence Effort | Labour hours required to prepare periodic evidence packs, measured before and after platform adoption. |

*Table 3: Pilot Success Metrics Framework*

## 9.2 Value Quantification Framework

A practical framework for constructing early-stage business cases is as follows: Total Value = (Utilisation Uplift × Throughput Value) + (Avoided Curtailment Cost) + (Reduced Manual Effort) + (Reduced Dispute and Audit Risk). The pilot should define baseline periods for each component and quantify using operator-provided operational data and current process effort measurements. This framework enables the demonstration of tangible, measurable returns to prospective investors and operator stakeholders.

# 10. Product Roadmap (v1–v3) and Interoperability Strategy

## 10.1 Version 1: Nominations and Constraints (MVP)

Entitlements register, forecast intake and validation, nomination workflow with cut-offs and approvals, constraint allocation (pro-rata baseline), notice generation and archiving, immutable audit logs, and reporting dashboards.

## 10.2 Version 2: Disruption Optimisation and MRV Evidence Packs

Probabilistic planning and advanced constraint-based optimisation; automated reconciliation across the capture-transport-storage chain; monitoring plan requirement mapping; automated evidence pack generation; and exception workflows for anomalous data or deviations.

## 10.3 Version 3: Certificate-Grade Assurance and Cross-Border Interoperability

Certificate issuance and lifecycle management workflows; lifecycle emissions breakdown support; interoperability across multiple T&S networks and jurisdictions; and portfolio-level optimisation across connected networks.

## 10.4 Interoperability Principles

The CCS Chain Optimizer's interoperability strategy is built upon four governing principles:

- Standardisation on canonical entities and time-aligned volume representations across all integrated systems.
- Preservation of provenance and quality state for every data record throughout the integration chain.
- Treatment of allocation rules and nomination cycles as configurable policy artefacts, enabling adaptation to evolving market frameworks.
- Exportable evidence packs and API-based integration to operator, verifier, and regulatory systems, ensuring compatibility with the broader CCS digital ecosystem.

## 11. Competitive Landscape and Differentiation

The contemporary CCS software ecosystem can be broadly categorised into three functional domains: (i) operational technology stacks—comprising SCADA systems, pipeline management systems, and terminal management platforms; (ii) bespoke reporting and integration solutions—including dashboards and point integrations developed for specific operator requirements; and (iii) emerging MRV and environmental integrity platforms—focused on compliance reporting, carbon credit documentation, and verification workflows.

Each of these categories addresses material operational needs within the CCS value chain. However, they typically operate within defined boundaries: OT systems excel within individual asset perimeters; bespoke reporting solutions address specific data needs without comprehensive workflow integration; and MRV platforms focus primarily on downstream compliance outputs rather than the upstream operational decisions that generate the data they report upon.

The gap that the CCS Chain Optimizer addresses is the multi-user operational-commercial interface: the layer at which entitlements, nominations, constraints, allocations, and auditable evidence must be orchestrated across organisational boundaries and integrated into a coherent, governed operating model.

The platform differentiates from existing solutions through three integrated capabilities:

- **Market-Aligned Operational Workflows:** Entitlements, nomination cycles, constraint notices, allocations, and renominations are implemented as first-class, governed workflows rather than the ad hoc spreadsheet and email-based processes that characterise the current operational environment (DESNZ, 2023, 2025).
- **Optimisation with Auditability:** Allocation and scheduling decisions are computed under explicit constraints and objectives, with the full decision artefact set retained to reproduce outcomes for audit and dispute resolution.
- **Assurance by Design:** Data provenance, quality-state tagging (measured/derived/estimated), and evidence pack generation are embedded from day one of platform operation, reducing the friction and cost associated with MRV and verification activities (EUR-Lex, 2018).

# 12. Commercial Model and Go-to-Market Strategy

## 12.1 Target Customer Segments

The CCS Chain Optimizer is designed for deployment across a defined customer ecosystem:

- **Primary:** $CO_2$ transport and storage operators (T&SCo) and cluster delivery organisations directly responsible for shared network operations.
- **Secondary:** Large industrial emitters and anchor users within CCS clusters, where curtailment risk to core industrial operations creates a material incentive to participate in or co-sponsor the development of optimised network operations.
- **Adjacent:** EPC, PMC, and systems integration firms supporting T&S operators through operational readiness programmes; and assurance and verification firms supporting MRV and carbon market activities.

## 12.2 Commercial Structure

The initial commercial model comprises three components:

- **Pilot Fee:** A fixed fee covering the 8–12 week pilot period, encompassing configuration, integration, validation rule development, user training, and formal acceptance evidence delivery.
- **Annual Subscription:** Recurring revenue priced by scale drivers including the number of users and delivery points, throughput band, and enabled functional modules. This structure enables the platform to scale commercially in line with network utilisation growth.
- **Professional Services:** Optional engagement for deeper integrations, custom reporting requirements, and extended MRV or certificate workflow development, priced on a project basis.

## 12.3 Go-to-Market Phases

The go-to-market strategy is structured in three geographic and capability phases:

- **Phase 1 — United Kingdom:** Pilot deployment with a UK cluster operator or early-stage T&S provider, focusing on the nominations and constraint allocation MVP. The UK regulatory environment provides the clearest near-term governance framework for shared T&S operations.
- **Phase 2 — Europe:** Replication and adaptation of the platform for European cross-border CCS chains, where interoperability and evidence capabilities represent key differentiators in an increasingly formalised market.
- **Phase 3 — Middle East:** Adaptation of the platform for regional operating models, which typically involve larger-scale, hub-based infrastructure, and for local data residency and sovereignty requirements.

## 12.4 Partnership Ecosystem

The CCS Chain Optimizer's commercial strategy incorporates a partnership approach across the value chain. Key partnership pathways include SCADA and historian technology providers, metering system vendors, engineering consultancies supporting T&S operational readiness, cloud and data platform providers, and assurance and verification firms. The Northern Lights collaboration with SLB and Microsoft represents a market signal that operator-led partnerships may constitute a preferred model for accelerating digital capability acquisition within the CCS sector (SLB, 2023; Northern Lights, 2023).

## 13. Risks, Limitations, and Mitigations

A comprehensive risk assessment has been undertaken across the principal domains of data, technology, operations, regulation, and security. The following table summarises the key risks identified and the corresponding mitigation strategies:

| Risk Category | Risk Description & Mitigation | Severity |
|---|---|---|
| **Data Access &** Quality | Inconsistent or incomplete data from upstream systems may impair platform accuracy. Mitigated through staged integration, robust validation rules, and clear data-sharing agreements. | High |
| **Model Risk &** Explainability | AI-generated recommendations may be opaque or unreliable. Mitigated through transparent optimisation logic, uncertainty reporting, version-controlled model governance, and mandatory approval workflows. | High |
| **Operational** Adoption | Users may resist adoption of new workflows or fail to engage with platform outputs. Mitigated through alignment to existing control-room processes, human-in-the-loop design, and structured training and playbook delivery. | Medium |
| **Regulatory** Evolution | Network Code and EU market rules may evolve in directions that require platform adaptation. Mitigated through configurable policy artefacts and continuous regulatory mapping (DESNZ, 2023, 2025). | Medium |
| **Cybersecurity** | Unauthorised access to commercially sensitive operational data. Mitigated through security-by-design, RBAC, encryption in transit and at rest, immutable audit logging, and regular independent security assurance. | High |

*Table 4: Risk Register Summary*

## 14. Conclusion

Carbon capture and storage networks in the United Kingdom and Europe are converging upon multi-user, regulated operating models that demand robust operational coordination, transparent allocation mechanisms, and auditable assurance across the full capture-transport-storage chain. The CCS Chain Optimizer is designed to become the digital operating layer that enables this transition: a repeatable, productised workflow system for nominations, constraints, and allocation, built upon a data backbone that supports MRV evidence generation and, where required, certificate-grade documentation.

The platform's alignment with the governance framework established by the UK CCS Network Code and Ofgem's enforcement guidance positions it for near-term deployment within the UK cluster environment, while its configurable, interoperable architecture provides a foundation for scaling into European cross-border chains and, subsequently, into the Middle East.

The recommended next step is the engagement of a UK cluster operator or T&S provider to commence the pilot discovery process, with a view to demonstrating the platform's capabilities within an 8–12 week pilot programme. The value case is strongest for those operators facing the most immediate pressure from shared capacity constraints and evolving verification expectations—conditions that are increasingly prevalent across the UK CCS landscape.

NEXERO invites prospective partners, investors, and operators to engage in further technical and commercial discussions regarding the CCS Chain Optimizer.

## Appendix A — Glossary of Key Terms

| Term | Definition |
|---|---|
| **CCS** | Carbon Capture and Storage. |
| **T&S / T&SCo** | Transport and Storage / Transport and Storage Company (the operator of the shared network). |
| **Nomination** | A user-submitted schedule or quantity request to deliver or inject $CO_2$ over a defined operational period. |
| **Constraint** | A period during which available network or storage capacity falls below aggregate demand or registered entitlements, necessitating allocation. |
| **MRV** | Monitoring, Reporting, and Verification — the framework of activities required to confirm that $CO_2$ has been captured, transported, and stored as claimed. |
| **Pro-Rata Allocation** | A proportional allocation mechanism in which available capacity during a constraint is distributed among affected users in proportion to their registered capacity or entitlement. |
| **Provenance** | Metadata describing the origin, transformations, validation status, and ownership of a data record throughout its lifecycle. |
| **SCADA** | Supervisory Control and Data Acquisition — the operational technology system used to monitor and control industrial processes. |
| **TEN-E** | Trans-European Networks for Energy — the EU framework governing cross-border energy infrastructure projects. |

## Appendix B — Canonical Data Model (High-Level Entities)

The minimum canonical data model for the MVP comprises the following entities and relationships:

- User / Shipper — the entity holding entitlements and submitting nominations.
- Delivery Point — the physical connection point and associated metering installation.
- Entitlement / Registered Capacity — time-bound capacity allocation by user and delivery point.
- Forecast Submission — multi-horizon forecast by user, with submission timestamp and validation status.
- Nomination / Renomination — daily or hourly quantity request, with status tracking and approval records.
- Constraint Event — time window, affected delivery points, and available capacity envelope.
- Allocation — per-user allocation output, with basis, calculation metadata, and approval record.
- Actuals — metered delivery, transport, and injection volumes, with reconciled totals.
- Notice / Communication — constraint notices, acceptance and rejection notices, and related communications archive.

## Appendix C — Pilot Discovery Checklist

A pilot discovery phase typically confirms the following items:

1. Network topology, delivery points in scope, and current nomination and communication processes.
2. Entitlement definitions and current contractual allocation rules, including constraint handling provisions.
3. Available data sources, integration access methods, and current data quality for metered flows and availability signals.
4. Operational constraints and safety/operability limits that must be respected by scheduling and allocation logic.
5. Governance requirements: approval processes, segregation of duties, audit record retention, and reporting cadence.
6. Success metrics and baseline definitions for utilisation, curtailment, and decision cycle times.

## Appendix D — Constraint Event Worked Example

This worked example illustrates the end-to-end processing of a constraint event through the CCS Chain Optimizer. All figures are illustrative; the purpose is to demonstrate the logic, governance artefacts, and operator outputs produced by the platform.

### Scenario

A transport segment becomes constrained for a 24-hour period. Available capacity is 800 $tCO_2$/day. Three users hold registered capacities of 500, 300, and 200 $tCO_2$/day respectively (total registered: 1,000 $tCO_2$/day). Each user nominates its full registered capacity. The baseline allocation rule is pro-rata allocation across constrained users.

### Step 1 — Constraint Envelope and Affected Parties

The platform establishes: constraint window (00:00–24:00, Day D); available capacity envelope (800 $tCO_2$/day); affected users (U1, U2, U3). Captured artefacts include the asset status snapshot, constraint rationale documentation, nominations received, and the available capacity calculation.

### Step 2 — Pro-Rata Allocation Computation

| User | Registered Capacity (t/day) | Pro-Rata Share | Allocated Capacity (t/day) |
|---|---|---|---|
| U1 | 500 | 500/1000 = 0.50 | 0.50 × 800 = 400 |
| U2 | 300 | 300/1000 = 0.30 | 0.30 × 800 = 240 |
| U3 | 200 | 200/1000 = 0.20 | 0.20 × 800 = 160 |

*Table 5: Pro-Rata Allocation Calculation*

### Step 3 — Operationalisation

The platform generates constraint notices to all affected users, prompts renominations to allocated capacity, and records operator approvals. If surplus reallocation is permitted under the configured rules, the platform applies the relevant reallocation logic and records the calculation basis and approvals.

### Evidence Outputs

The platform produces: (i) notice and publication records; (ii) the allocation worksheet with full calculation detail; (iii) accepted renominations; (iv) deviation monitoring outputs; and (v) post-event reconciliation linking nominations, allocations, and metered actuals.

## Appendix E — Minimum Viable Data Dictionary

The following table defines the minimum viable dataset for piloting the nominations and constraints MVP. Each field is stored with provenance metadata and a quality-state label as described in Section 6.

| Domain | Field | Granularity | Quality State | Purpose |
|---|---|---|---|---|
| Entitlements | Registered Capacity (versioned) | As-defined | Administrative | Allocation baseline |
| Nominations | Day-ahead (hourly) | Hourly | Measured | Feasibility & constraint handling |
| Capture | Delivered $CO_2$ Mass Flow | 5–60 min | Measured | Actuals vs nominations |
| Transport | Available Capacity Envelope | Event/Daily | Derived | Constraint detection |
| Transport | Compressor Status + Outage | Event | Measured | Constraint drivers |
| Storage | Injection Availability | Event/Daily | Derived | Feasibility & rescheduling |
| Governance | Constraint Notice Record | Per Event | System | Auditability & compliance |

*Table 6: Minimum Viable Data Dictionary*

## Appendix F — MRV-Ready Evidence Pack Structure

The Evidence Engine produces evidence packs structured to align with EU CCS Directive monitoring requirements (EUR-Lex, 2018) and operator-specific monitoring plans. The illustrative structure of a complete evidence pack is as follows:

1. **Executive Summary** — Period covered, scope definition, and key events.
2. **System Boundary and Monitoring-Plan Mapping** — Included and excluded scope elements, instrumentation list, and mapping to approved monitoring plan requirements.
3. **Metering and Data Provenance Register** — Sources, transformations applied, quality flags, and quality-state labels for all data inputs.
4. **Nominations and Allocations Log** — Complete record of constraint events, notices issued, allocation calculations, and approvals.
5. **Delivered vs Nominated vs Stored Reconciliation** — Time-series comparison, totals, and documented gap-handling methodology.
6. **$CO_2$ Quality and Specification Compliance Summary** — Where applicable, confirmation of delivered $CO_2$ against specification requirements.
7. **Exception Register** — Anomalies identified, overrides applied, investigations undertaken, and closure records.
8. **Verification Artefacts** — Sign-offs, version history, and retained source links.
9. **Audit Log** — Immutable record of all changes and approvals throughout the evidence pack lifecycle.

## References

DESNZ (2023). *Carbon Capture and Storage (CCS) Network Code: Heads of Terms Consultation.* UK Government, Department for Energy Security and Net Zero. Available at: https://www.gov.uk/government/consultations/carbon-capture-and-storage-ccs-network-code-updated-heads-of-terms [Accessed: 19 December 2025].

DESNZ (2025). *CCS Network Code: Updated Framework.* UK Government, Department for Energy Security and Net Zero. [Accessed: 19 December 2025].

European Commission (2025). Commission Launches Public Consultation on $CO_2$ Markets and Infrastructure, 6 October 2025. Available at: https://energy.ec.europa.eu/news/commission-launches-public-consultation-co2-markets-and-infrastructure-2025-10-06_en [Accessed: 19 December 2025].

European Commission (n.d.). *Industrial Carbon Management.* Available at: https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/industrial-carbon-management_en [Accessed: 19 December 2025].

European Commission (n.d.). *The EU's 2030 Carbon Storage Target (Net-Zero Industry Act).* Available at: https://climate.ec.europa.eu/eu-action/industrial-carbon-management/eus-2030-carbon-storage-target_en [Accessed: 19 December 2025].

EUR-Lex (2018). *Directive 2009/31/EC on the Geological Storage of Carbon Dioxide (Consolidated Version).* Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0031 [Accessed: 19 December 2025].

Northern Lights JV (2023). Northern Lights Collaborates with SLB and Microsoft to Digitalise Carbon Capture and Storage Value Chain. Available at: https://norlights.com/news/northern-lights-collaborates-with-slb-and-microsoft-to-digitalise-carbon-capture-and-storage-value-chain/ [Accessed: 19 December 2025].

Northern Lights JV (2025). Northern Lights Has Issued First $CO_2$ Storage Certificates. Available at: https://norlights.com/news/northern-lights-has-issued-first-co2-storage-certificates/ [Accessed: 19 December 2025].

Ofgem (2024). *$CO_2$ Transport and Storage Enforcement Guidelines.* Available at: https://www.ofgem.gov.uk/sites/default/files/2024-09/CO2_Transport_and_Storage_Enforcement_Guidelines.pdf [Accessed: 19 December 2025].

SLB (2023). SLB Collaborates with Northern Lights JV and Microsoft. Available at: https://www.slb.com/news-and-insights/newsroom/press-release/2023/slb-collaborates-with-northern-lights-jv-and-microsoft [Accessed: 19 December 2025].