



Hub-Only Pipeline Topology Architecture Standard Version 1.31(HOPT-ASv1.31)

Author: Arnab Sinha

July 2026

*System Architecture and Assurance Standard for Carbon Capture
Utilization and Storage (CCUS) Systems*

इति परमम्

Iti paramam

The content of this document is the intellectual property of **Novonanmek Material Sciences Private Limited** ("Novonanmek"). The user accepts that, without prior written consent from Novonanmek, no party other than Novonanmek or its authorized licensees may use this document—in whole or in part — to issue, represent, or provide official **Dynamic Compliance Evaluations, Dynamic Compliance determinations**, or any other official recognition under the HOPT-AS framework, whether for payment or free of charge. Novonanmek is not responsible for the consequences arising from any use of this document by others, including any interpretation or application of its Architecture Principles or Rules independently of the Dynamic Compliance framework established by this Standard.

NOVONANMEK MATERIAL SCIENCES PRIVATE LIMITED

DOCUMENT REVISION HISTORY

(Informative — Non-Normative)

Version HOPT-ASv1.31 — July 2026

Version HOPT-ASv1.21 — June 2026

Version HOPT-ASv1.11 — May 2026

Version HOPT-AS v1.1 — April 2026

This version introduces Dynamic Compliance and Real-Time Stewardship provisions to support multi-stakeholder and multi-phase deployment of HOPT-aligned infrastructure. These additions establish continuous architectural alignment during system expansion and define governance mechanisms for preserving topology integrity over time.

The updates in this version include:

- Introduction of Dynamic Compliance framework for evolving HOPT deployments
- Addition of Real-Time Stewardship requirements for multi-phase infrastructure development
- Definition of Static Compliance and Dynamic Compliance layers
- Establishment of Cluster Architecture Steward role
- Scope definition for stewardship across hub siting, logistics, pipelines, and cluster evolution
- Preservation rules for future topology and backbone expansion
- Certification tier distinction between HOPT-Design Certified and HOPT-Stewardship Certified
- Conditions for loss of Dynamic Compliance and certification downgrade

These changes enhance long-term architectural assurance while maintaining compatibility with previously defined HOPT topology, boundary, and participation requirements.

Version HOPT-AS v1.0 — January 2026

Initial release of the Hub-Only Pipeline Topology Architecture Standard (HOPT-AS)

Contents

Foreword And Preface: Origin, Purpose, and Evolution of HOPT-AS	1
Executive Summary	3
Assurance Statement	4
Contact Information	5
Document Governance	
Copyright and Ownership Statement	7
Status and Release Note	8
Governance, Ownership, and Authority Model	9
Terms Of Use	10
Technical Foundations	
Hub Only Pipeline Topology (HOPT) – Concept Overview	18
Architectural Risk and Long-Term Infrastructure Value	21
Architectural Drift and Dynamic Compliance	25
Dynamically Preserved Architectures	28
Real-Time Stewardship and Dynamic Compliance	29
Relevance Of Dynamic Compliance to MRV And Chain of Custody	30
Reader’s Guide — Structure and Use of This Standard	31
How To Use This Standard	33
Normative Sections	
Section 1 — Introduction & Purpose	39
Section 2 — Foundational Principles Of HOPT-AS	45
Section 3 — Stakeholder Model and Domain Responsibilities	51
Section 4 — System Boundaries & Domain Interfaces	58
Section 5 — Topology Classes & Allowed Configurations	65
Section 6 — Participation And Dynamic Compliance Requirements	71

Section 7 — Deployment Models & Scaling Behaviour	74
Section 8 — MRV, Carbon Accounting & Chain-of-Custody Framework	80
Section 9 — Dynamic Compliance and Architectural Conformance	88
Section 10 — HOPT-AS Certification Framework	95
Section 11 — Governance, Updates, and Interpretation Framework	100
Section 12 — Glossary, Definitions & Terminology	104
Section 13 — Safety & Regulatory Considerations	109
Section 14 — Informative Annexes	111
References	113
Annex A: Integration Pathways for Diverse Carbon Capture Technologies	114
Annex B: Energy Infrastructure Implementation Program (EIIP)	117

FOREWORD AND PREFACE: ORIGIN, PURPOSE, AND EVOLUTION OF HOPT-AS

The Hub-Only Pipeline Topology Architecture Standard (HOPT-AS) originated from the recognition that relocating gaseous CO₂ handling from individual emitting facilities to centralized regeneration hubs fundamentally changes the scalability, permitting feasibility, risk allocation, and economics of Carbon Capture, Utilization, and Storage (CCUS) systems in regions with geographically dispersed industrial emissions.

By enabling emitters to participate through the transport of solid carbon carriers rather than direct pipeline connections, HOPT-AS replaces the conventional emitter-to-pipeline model with a hub-only pipeline network in which gaseous CO₂ is generated, conditioned, and transported exclusively from centralized hubs. This architectural approach reduces infrastructure complexity, lowers barriers to participation, and enables scalable deployment through shared regional infrastructure.

As development of HOPT-AS progressed, it became evident that defining an architecture alone was insufficient to ensure its long-term value. Unlike conventional infrastructure systems whose physical connections remain relatively static, HOPT-AS is an open architecture in which emitter participation, hub assignments, logistics pathways, and supporting infrastructure may evolve continuously throughout the operational life of the system. This operational flexibility is a defining characteristic of HOPT-AS and is fundamental to its scalability.

However, the same flexibility that enables scalable deployment also introduces the possibility of **Architectural Drift**, whereby incremental infrastructure changes may progressively erode the defining characteristics and system-level benefits of the architecture. Preserving the architectural identity of HOPT-AS therefore requires more than initial conformance; it requires the continuous preservation of the architectural principles upon which HOPT-AS is founded.

This realization led to the development of **Dynamic Compliance**, a mandatory architectural requirement that continuously preserves the defining characteristics of HOPT-AS as infrastructure evolves. Rather than treating compliance as a one-time assessment, HOPT-AS establishes Dynamic Compliance as an integral characteristic of every Architecture Class defined by this Standard, ensuring that operational evolution remains consistent with the governing principles of the Hub-Only Pipeline Topology throughout the infrastructure lifecycle.

Accordingly, HOPT-AS establishes a family of **Dynamically Preserved Architectures (DPAs)**. Each Architecture Class defined by this Standard derives its continuing architectural identity not only from its initial design but also from the ongoing preservation of the

structural characteristics through which it mitigates system-level risks, enables scalability, maintains interoperability, and supports long-term infrastructure development.

The Hub-Only Pipeline Topology Architecture Standard (HOPT-AS) therefore extends beyond the definition of an infrastructure topology. It establishes a comprehensive architectural framework governing the design, evolution, and long-term preservation of HOPT-AS systems through clearly defined Architecture Classes, mandatory Dynamic Compliance requirements, and Real-Time Stewardship for preserving architectural integrity as infrastructure expands.

HOPT-AS has been developed to support governments, industrial operators, infrastructure developers, logistics providers, pipeline operators, storage operators, financiers, insurers, regulators, and other stakeholders seeking a coherent, scalable, and interoperable framework for long-term CCUS deployment.

This Standard defines architectural principles, stakeholder responsibilities, system boundaries, topology rules, and Dynamic Compliance requirements. It is not intended to replace detailed engineering design, project-specific safety analysis, regulatory approvals, or statutory compliance. Such activities remain the responsibility of implementers and competent authorities, provided they remain consistent with the architectural requirements established by HOPT-AS.

HOPT-AS is maintained by Novonanmek Material Sciences Private Limited as the originator, owner, and steward of the Standard. The Standard will continue to evolve through controlled revisions and formal interpretations reflecting implementation experience, technological advancement, and the continued evolution of the Hub-Only Pipeline Topology.

EXECUTIVE SUMMARY

HOPT-AS establishes a comprehensive architectural framework for scalable Carbon Capture, Utilization, and Storage (CCUS) deployment in regions where conventional emitter-connected pipeline networks are impractical. By relocating gaseous CO₂ handling from individual emitting facilities to centralized regeneration hubs and limiting pipeline connections to hubs, HOPT-AS lowers infrastructure barriers, enables shared facilities, and supports scalable deployment through hub-based networks.

The Hub-Only Pipeline Topology Architecture Standard (HOPT-AS) is an open architecture. Emitters participate through flexible solids logistics rather than fixed pipeline connections, allowing infrastructure to expand through the addition of new emitters, hubs, logistics pathways, and supporting facilities without altering the fundamental hub-only pipeline topology. This operational flexibility is a defining characteristic of HOPT-AS and enables long-term, phased deployment across diverse industrial regions.

Because open architectures continuously evolve, HOPT-AS introduces **Dynamic Compliance** as a mandatory architectural requirement. Rather than treating compliance as a one-time assessment, Dynamic Compliance continuously preserves the defining characteristics of each HOPT-AS Architecture Class, preventing Architectural Drift and ensuring that infrastructure evolution remains consistent with the governing principles of the standard.

HOPT-AS therefore defines a family of **Dynamically Preserved Architectures**, whose architectural identity is maintained throughout the operational lifecycle of the infrastructure system. Through Dynamic Compliance and Real-Time Stewardship, HOPT-AS preserves topology integrity, interoperability, scalability, and the system-level risk-mitigation characteristics upon which the architecture is founded, while remaining independent of asset ownership, engineering design, and operational control.

By combining a hub-only pipeline topology with continuous architectural preservation, HOPT-AS provides a framework for deploying, expanding, and governing CCUS infrastructure as a coherent, living architecture capable of supporting long-term industrial decarbonization.

ASSURANCE STATEMENT

HOPT-AS provides architectural assurance by defining mandatory Architecture Classes whose defining characteristics are continuously preserved through Dynamic Compliance.

Unlike conventional architecture standards, which primarily assess conformance at a particular point in time, HOPT-AS recognizes that CCUS infrastructure evolves continuously. Architectural assurance therefore depends not only on initial conformance but also on the continued preservation of the defining characteristics of the applicable Architecture Class throughout the infrastructure lifecycle.

Accordingly, assurance under HOPT-AS is founded upon governance, Dynamic Compliance, and the prevention of Architectural Drift, thereby preserving the long-term integrity, interoperability, scalability, and risk-mitigating characteristics of the Hub-Only Pipeline Topology.

CONTACT INFORMATION

All correspondence relating to this Standard, including requests for clarification, certification inquiries, or licensing discussions, shall be directed to:

Email:

(1) info@novonanmek.com

(2) foundersoffice@novonanmek.com

These contact points represent Novonanmek in its capacity as owner and authority of HOPT-AS.

Document Governance

COPYRIGHT AND OWNERSHIP STATEMENT

© 2026 Novonanmek Material Sciences Private Limited. All rights reserved.

This document, titled **Hub-Only Pipeline Topology Architecture Standard version 1.31 (HOPT-ASv1.31)**, including all architectural principles, topology definitions, system boundaries, stakeholder models, compliance rules, certification concepts, terminology, and related materials, is the intellectual property of Novonanmek Material Sciences Private Limited (“Novonanmek”).

All rights, title, and interest in and to this Standard are retained by Novonanmek. No transfer, license, or assignment of intellectual property rights is granted except as expressly stated in this document.

No part of this publication may be reproduced, distributed, transmitted, translated, stored in a retrieval system, or incorporated into other works, in any form or by any means, without prior written permission from Novonanmek, except as expressly permitted under the Terms and Conditions of Use set forth herein.

STATUS AND RELEASE NOTE

This document is released as HOPT-AS v1.31, a comprehensive architecture and assurance standard defining the Hub-Only Pipeline Topology (HOPT) for carbon capture, transport, utilization, and storage (CCUS) systems

HOPT-AS is founded on the principle that the value of an architecture lies not only in its initial definition, but in the continued preservation of the architectural characteristics through which it mitigates system-level risks. Accordingly, HOPT-AS establishes Dynamic Compliance as the governing mechanism for preserving the architectural integrity of the Hub-Only Pipeline Topology throughout the lifecycle of evolving CCUS infrastructure.

HOPT-AS v1.31 is intended for voluntary use by industry participants, infrastructure developers, financiers, insurers, regulators, and other stakeholders seeking a structured, auditable, and scalable architectural framework for CCUS deployment.

This release is authoritative as issued by Novonanmek. All official interpretations, certifications, scoring, and compliance determinations related to HOPT-AS are administered by Novonanmek as the originator, owner and steward of the standard or by parties expressly authorized by it.

GOVERNANCE, OWNERSHIP, AND AUTHORITY MODEL

(Normative)

HOPT-AS is a comprehensive architecture and assurance standard. Novonanmek Material Sciences Private Limited is the originator, owner, and official steward of the HOPT-AS standard.

As steward, Novonanmek is responsible for:

- Publishing and maintaining the authoritative version of HOPT-AS
- Issuing formal interpretations and clarifications for certification purposes
- Defining compliance criteria and certification schemes
- Administering official certification marks and conformity claims
- Managing version control and revisions
- Overseeing the integrity of the standard

States, Industrial Development Corporations (IDCs), developers, and other stakeholders are encouraged to freely adopt, reference, customize, and implement the HOPT architecture principles and topology rules in their CCUS projects and policies.

Official certification, registry participation, and use of protected HOPT-AS marks shall be administered by Novonanmek or its expressly authorized partners. This ensures consistency, interoperability, and long-term integrity of the framework across implementations.

TERMS OF USE

(Normative)

1. Purpose and Scope

This document constitutes the **Hub-Only Pipeline Topology Architecture Standard (HOPT-AS)**.

HOPT-AS is a comprehensive Carbon Capture Utilization & Storage (CCUS) architecture and assurance standard. Novonanmek Material Sciences Private Limited (“Novonanmek”) is the originator, owner, and official steward of the HOPT-AS standard.

The Standard is made publicly available for the purpose of enabling reference, evaluation, design, and implementation of systems consistent with the Hub-Only Pipeline Topology (HOPT) architecture.

HOPT-AS defines architectural principles, mandatory topology rules, system boundaries, and interoperability requirements.

This Standard does not itself grant certification, trademark rights, registry participation, regulatory approval, or patent licenses.

2. Permitted Uses & Implementation Restrictions

Subject to applicable intellectual property rights and patent licensing obligations, any individual or entity may, without prior permission:

- Read, consult, and reference this Standard for educational, academic, planning, and non-commercial research purposes;
- Reference HOPT architectural concepts and terminology in technical, regulatory, financial, or planning documentation;
- Evaluate existing or proposed systems for conceptual alignment with HOPT-AS requirements.

2.1 The Multi-Party Infrastructure Initiation Mandate

Because the deployment of a Hub-Only Pipeline Topology is a multi-billion-dollar sovereign-scale infrastructure endeavour involving complex, multi-decade macro-coordination across independent industrial carbon emitters, transport pipeline operators, EPC contractors, and geological storage/utilization sites, a physical HOPT-AS deployment cannot execute in a regulatory or administrative vacuum.

We restrict and govern the right to formally initiate, organize, or register a physical infrastructure project under the HOPT-AS framework through the following provisions:

- **The Licensed Project Initiator (LPI) Requirement:** A physical HOPT-AS project can only be initiated by an entity explicitly chosen, authorized, and designated by Novonanmek Material Sciences Private Limited. This designated entity shall be formally known as a Licensed Project Initiator (LPI). No individual, consortium, or unauthorized corporate body may formally launch, represent, or mobilize a regional hub cluster as an active HOPT-AS project without this direct, explicit designation. *The active coordination tenure of the LPI shall continue from project inception until the formal commencement of commercial operations and the activation of live Dynamic Compliance over the physical assets.*
- **Mandatory Licensing Gateway:** To activate this designation, the entity chosen by Novonanmek must secure an official, non-transferable HOPT-AS Commercial License. Execution of a physical project without an active, fully paid license code registered on Novonanmek's ledger constitutes an absolute material breach of these Terms and a violation of Novonanmek's intellectual property.
- **Commercial Self-Sufficiency:** To maximize market agility and empower well-connected industry facilitators, Novonanmek establishes no strict pre-existing asset-ownership or upfront capital infrastructure prerequisites for obtaining an LPI credential. However, an LPI must operate under its own viable commercial business model and possess the independent financial capacity to fully cover its own operational expenditures.
- **New Structural Risk Allocation:** An LPI is entirely responsible for their own corporate risk, expenditures, and consortium management. Novonanmek bears zero liability for local project execution or financial shortfalls on the ground.
- **Unauthorized Configurations:** Any multi-party cluster assembled or mapped out without an active LPI license and registration ID from Novonanmek is legally unauthorized. It is automatically disqualified from receiving official HOPT-Design Certification or HOPT-Stewardship Certification, rendering it entirely legally invalid for claiming compliance in capital prospectuses, government grant applications or environmental filings.

3. Intellectual Property and Patent Rights

Elements of HOPT-AS may be covered by issued patents or pending patent applications held by Novonanmek or by third parties.

Publication of this Standard does **not** grant any patent license, express or implied.

Where Novonanmek owns or controls patent claims that are essential to the implementation of mandatory provisions of HOPT-AS, such claims may be licensed separately under the Patent Policy and Licensing Commitment set out below.

Certification under this Standard confirms architectural conformance only and **does not itself constitute a patent license**.

4. Patent Policy and Licensing Commitment

a. Standard-Essential Patent Claims (SEPs)

A **Standard-Essential Patent Claim (SEP)** is any patent claim that is necessarily infringed by a compliant implementation of a mandatory requirement of HOPT-AS, where no technically feasible non-infringing alternative exists within the Standard.

b. Licensing Commitment

Novonanmek commits that any patent claims **owned or controlled by Novonanmek** that are essential to implementing mandatory portions of HOPT-AS shall be made available for licensing on **Fair, Reasonable, and Non-Discriminatory (FRAND)** commercial terms.

This commitment:

- Applies to all implementers of HOPT-AS, irrespective of geography, sector, or business model;
- Binds Novonanmek and any successors-in-interest to such patent claims (the commitment runs with the patents);
- Is intended to promote broad adoption while enabling fair compensation for essential innovations.

c. Scope of Commitment

This FRAND commitment applies **only** to patent claims essential to mandatory provisions of HOPT-AS.

It does **not** apply to:

- Optional or informative portions of the Standard;
- Proprietary implementation details;
- Non-essential improvements, optimizations, or extensions;
- Trademarks, certification marks, conformity claims, or registry participation rights.

d. No Automatic License

Publication of this Standard does not itself grant a patent license.

Implementers seeking to practice patented portions of HOPT-AS must obtain licenses directly from the relevant patent holder under applicable terms.

e. Certification Is Separate from Licensing

Patent licensing and certification are independent processes:

- A patent license does not imply certification;
- Certification does not grant a patent license.

Certification confirms architectural conformity only.

f. Third-Party Patents

Novonanmek takes no position regarding patents owned by third parties.

Implementers are solely responsible for identifying and obtaining any necessary licenses from third-party patent holders.

g. Declaration and Transparency

Novonanmek may maintain a public list or database of declared Standard-Essential Patent Claims under its control.

Patent holders contributing to HOPT-AS are encouraged, but not required, to declare potential SEPs to promote transparency.

5. Certification, Trademarks, and Registry Rights

Certification, compliance designation, registry participation, and use of HOPT-related certification marks, labels, or claims are **separate from implementation rights** and are governed exclusively by **Novonanmek**.

Only Novonanmek, or auditors expressly authorized by Novonanmek, may:

- Issue HOPT compliance or certification determinations;
- Conduct or validate audits under the HOPT framework;
- Maintain official registries, serialized custody records, or market-eligibility determinations;
- Authorize use of HOPT certification marks, logos, or conformity claims.

No person or entity may claim “**HOPT-Certified**,” “**HOPT-Compliant**,” or equivalent status without formal certification issued by Novonanmek.

6. No Automatic License

Publication of this Standard does not itself grant a patent license.

Any required patent licenses must be obtained directly from the applicable patent holder under agreed terms.

7. Prohibited Uses

Without express written authorization from Novonanmek, no person or entity may:

- Implement HOPT-AS without being an Authorized Licensed Project Initiator (LPI)
- Falsely claim certification, compliance, or registry inclusion;
- Use HOPT certification marks, logos, or designations;
- Operate or promote derivative certification, registry, or governance schemes under the HOPT name;
- Misrepresent non-conforming systems as HOPT-compliant;
- Present unofficial interpretations as authoritative.

These restrictions apply to **certification, representation, and claims**, not to independent implementation of the architecture.

8. Interpretations and Clarifications

Novonanmek is the originator, owner and steward of this standard responsible for issuing formal interpretations, clarifications, or guidance regarding HOPT-AS.

Stakeholders may submit questions or proposals; however, only interpretations issued or endorsed in writing by Novonanmek are authoritative for certification or compliance purposes.

Independent technical analysis or implementation choices do not constitute official interpretations of the Standard.

9. Updates and Versioning

Novonanmek may issue revised, superseded, or withdrawn versions of HOPT-AS from time to time.

- New certifications apply the current version unless otherwise specified;
- Existing certified systems may be subject to transition or grandfathering provisions defined by Novonanmek;
- Use of superseded versions for new certification claims is not permitted unless expressly authorized.

10. Compliance and Enforcement

(Normative)

Implementations claiming conformity with HOPT-AS shall maintain Dynamic Compliance with the applicable Architecture Class throughout the operational lifecycle of the infrastructure system.

Participants are responsible for:

- maintaining compliance with the normative requirements of HOPT-AS;
- preserving the defining architectural characteristics of the applicable Architecture Class;
- providing information reasonably necessary to demonstrate continued Dynamic Compliance, where such claims are made; and
- refraining from representing an implementation as HOPT-conforming where Dynamic Compliance is no longer maintained.

Where Dynamic Compliance is not maintained, the implementation shall not be represented as conforming to HOPT-AS or as operating as a Dynamically Preserved Architecture.

Novonanmek may issue determinations, interpretations, or compliance findings concerning the application of this Standard. Any public claim of conformity with HOPT-AS shall be consistent with such determinations and with the requirements of this Standard.

Nothing in this section restricts the right of any person or organization to design, develop, or operate infrastructure based upon the architectural concepts described in HOPT-AS. However, only implementations that maintain Dynamic Compliance with the applicable Architecture Class may be represented as conforming to HOPT-AS.

11. No Warranty; No Guarantee

HOPT-AS is provided “**as is**”, without warranty of any kind.

Novonanmek makes no representation regarding fitness for purpose, regulatory acceptance, commercial viability, or freedom from third-party intellectual property claims.

Implementers are solely responsible for compliance with applicable laws, regulations, safety requirements, and licensing obligations.

12. Ownership and Authority

HOPT-AS is an architecture and assurance standard owned and stewarded by Novonanmek Material Sciences Private Limited.

As the originator and official steward of the standard, Novonanmek maintains the authoritative version and is responsible for official certification, registry management, interpretations, and overall integrity of the framework.

No entity, consortium, regulator, association, or other body may represent itself as the governing authority, certification body, or official registry operator for HOPT-AS without the express written authorization of Novonanmek. Unauthorized certification or governance activities have no validity under the HOPT-AS framework.

Technical Foundations

HUB ONLY PIPELINE TOPOLOGY (HOPT) – CONCEPT OVERVIEW

(Informative — Non-Normative)

1. Purpose of This Overview

This section provides a concise, non-normative explanation of the **Hub-Only Pipeline Topology (HOPT)** for readers encountering the concept for the first time. It is intended to explain *what HOPT is, why it exists, and how it fundamentally differs from conventional carbon capture and storage (CCUS) architectures.*

This overview does **not** define requirements, constraints, or compliance rules. Normative requirements are defined elsewhere in this standard.

2. Core Concept

The Hub-Only Pipeline Topology (HOPT) is an architectural approach to carbon capture, transport, and storage in which **gaseous CO₂ pipelines connect only centralized hubs, not individual emitting facilities.**

In HOPT:

- CO₂ is captured at emitting sites in **solid-bound form** using solid-looping capture technologies.
- The CO₂-laden solids are transported using conventional logistics (road, rail, barge, or equivalent) to centralized **regeneration hubs**.
- At the hubs, the solids are regenerated, releasing gaseous CO₂ and producing reusable solid sorbent.
- The regenerated sorbent is returned to emitters for reuse.
- The assignment of emitters to hubs is operationally flexible and may evolve over time through solids logistics without requiring changes to the hub-only pipeline network, provided the governing architectural principles of HOPT are continuously preserved.
- **Only the hubs** handle gaseous CO₂ and connect to CO₂ pipelines.
- Pipelines therefore form a **hub-to-hub network**, rather than an emitter-to-pipeline network.

As a result, emitting facilities do not manage gaseous CO₂, do not connect to CO₂ pipelines, and do not require onsite compression or pipeline tie-ins.

3. Why HOPT Is Needed

Conventional CCUS architectures typically require each emitter to connect directly to a CO₂ pipeline network. This model faces significant barriers in many regions, including:

- Absence of existing CO₂ pipeline infrastructure
- Complex, multi-jurisdictional permitting for linear pipelines
- High capital cost of compression, dehydration, and tie-ins at each emitter
- Difficulty onboarding small and medium emitters
- Long deployment timelines and fragmented infrastructure build-out

HOPT addresses these challenges by **relocating gaseous CO₂ handling from emitters to hubs**, enabling participation without pipeline connectivity at the emission source.

4. Key Architectural Characteristics

The defining characteristics of the HOPT concept are:

- **Emitter Exclusion from Pipelines**
Emitters never inject, handle, or interface with pipeline-grade CO₂.
- **Centralized Regeneration and Compression**
All CO₂ release, conditioning, and compression occur at certified hubs.
- **Solids-Based Logistics Interface**
Emitters interact with the system exclusively through the transport of solid carbon carriers.
- **Hub-Only Pipeline Network**
CO₂ pipelines connect hubs to hubs (and onward to storage or utilization), not to emitters.
- **Shared, Multi-Emitter Infrastructure**
Each hub serves multiple emitters, enabling economies of scale and standardized participation.
- **Dynamic Logistics Connectivity**
Emitters participate through flexible solids logistics rather than fixed pipeline connections. Emitter-to-hub relationships may evolve over time in response to operational, commercial, or infrastructure considerations while preserving the Hub-Only Pipeline principle.

5. System-Level Benefits

By restructuring where and how CO₂ is handled, HOPT delivers several system-level advantages:

- Significant reduction in total pipeline length compared to emitter-connected networks
- Lower entry barriers for emitters of all sizes
- Faster deployment using existing transport infrastructure
- Reduced permitting complexity at industrial sites
- Improved scalability through shared hubs and repeatable architectures
- Clear separation of stakeholder responsibilities and risk domains

These benefits make HOPT particularly suitable for regions with dispersed industrial emitters and limited pipeline legacy infrastructure.

6. From Concept to Governed Architecture

While the HOPT concept defines a topology, large-scale deployment requires more than a conceptual description. Real-world implementation demands:

- Clear system boundaries
- Defined stakeholder roles
- Rules for allowed and forbidden configurations
- Scalable topology classes
- Governance, certification, and registry mechanisms

The Hub-Only Pipeline Topology Architecture Standard (HOPT-AS) provides this structure. It formalizes the HOPT concept into a governed, interoperable, and certifiable architecture suitable for regional and national CCUS deployment. Because HOPT is an open architecture in which emitter participation and logistics relationships may evolve over time, HOPT-AS also establishes Dynamic Compliance to ensure that infrastructure evolution preserves the defining architectural characteristics and long-term integrity of the Hub-Only Pipeline Topology.

7. Relationship to the Rest of This Standard

This overview explains the *idea* of HOPT. Subsequent sections of HOPT-AS define:

- Mandatory topology principles
- System boundaries and interfaces
- Stakeholder responsibilities
- Allowed topology classes
- Participation, certification, and compliance requirements

Readers seeking formal requirements should refer to the normative sections that follow.

ARCHITECTURAL RISK AND LONG-TERM INFRASTRUCTURE VALUE

(Informative — Non-Normative)

1. Architecture as a Long-Term Infrastructure Asset

Large-scale infrastructure investments are expected to operate safely, efficiently, and economically over several decades. During this period, infrastructure systems rarely remain static. New participants enter the network, demand patterns evolve, ownership changes, technologies mature, and additional infrastructure is developed by multiple independent stakeholders.

Accordingly, the long-term value of infrastructure depends not only upon the technical performance of individual assets, but also upon the architecture within which those assets operate and evolve.

Conventional project appraisal appropriately evaluates engineering feasibility, construction risk, commercial viability, environmental and social impacts, regulatory compliance, and financial performance. These assessments determine whether an individual project is suitable for development and operation.

However, they do not ordinarily evaluate whether the underlying infrastructure architecture will continue to preserve its defining characteristics and long-term value as the surrounding infrastructure ecosystem expands and evolves.

This gives rise to a distinct category of infrastructure risk: **Architectural Risk**.

Architectural Risk is the risk that infrastructure which is technically sound, commercially viable, and fully functional at the time of deployment may progressively lose long-term value because its architecture cannot efficiently accommodate future expansion, additional participants, evolving logistics, changing demand patterns, or coordinated regional development.

Accordingly, infrastructure architecture should be regarded as a legitimate dimension of long-term investment risk alongside technical, financial, environmental, regulatory, legal, and commercial considerations.

2. Why Architectural Risk Matters

Poor architectural decisions rarely result in immediate project failure. Instead, their consequences typically emerge gradually as infrastructure ecosystems evolve over many years.

Architectural deficiencies may result in:

- infrastructure fragmentation;
- duplication of major assets;
- stranded infrastructure;
- reduced asset utilization;
- constrained future expansion;
- incompatible infrastructure development;
- increased coordination complexity;
- reduced interoperability;
- higher lifecycle capital expenditure; and
- erosion of long-term infrastructure value.

These are system-level risks. They arise from the structure and evolution of the infrastructure ecosystem rather than from the performance of individual assets.

3. Architectural Risk and Conventional Due Diligence

Conventional infrastructure due diligence evaluates whether a project is technically feasible, financially viable, legally compliant, environmentally acceptable, and capable of safe operation. These assessments remain essential and are not replaced by HOPT-AS.

HOPT-AS addresses a complementary question:

Will the infrastructure architecture continue to preserve its defining characteristics and long-term value as the infrastructure ecosystem evolves throughout its operational life?

Accordingly, HOPT-AS should be understood as an **architectural governance framework** that complements existing engineering, financial, legal, environmental, regulatory, and commercial due diligence by addressing long-term Architectural Risk through the continuous preservation of the applicable Architecture Class.

Typical due diligence disciplines therefore address complementary questions:

Assessment Discipline	Primary Question Addressed
Engineering	Can the infrastructure be safely designed, constructed, and operated?
Financial	Is the project commercially and financially viable?
Legal	Are ownership, contractual, and regulatory arrangements appropriate?
Environmental & Social	Are environmental and social risks appropriately managed?
Geological / Storage	Is long-term CO ₂ storage technically suitable?
Architecture (HOPT-AS)	Will the infrastructure architecture remain coherent, interoperable, scalable, and dynamically preserved as the infrastructure ecosystem evolves?

4. Architectural Risk Categories

The following categories of Architectural Risk commonly influence the long-term performance and value of infrastructure systems.

Architectural Risk	Why Investors and Infrastructure Owners Care	HOPT-AS Response
Infrastructure Fragmentation	Independent developments may fail to integrate into larger infrastructure systems, reducing long-term network value.	Common Architecture Classes, standardized topology, system boundaries, and interoperability requirements.
Infrastructure Duplication	Replicated processing or transport infrastructure increases capital intensity and reduces asset efficiency.	Shared hub infrastructure and centralized regeneration architecture.
Stranded Asset Risk	Dedicated infrastructure may lose value as participation patterns evolve.	Shared infrastructure, modular Architecture Classes, and flexible participation.
Scalability Risk	Infrastructure designed only for initial deployment may require costly redesign as participation grows.	Standardized Architecture Classes supporting structured expansion.
Expansion Compatibility Risk	Future infrastructure may be difficult to integrate into existing systems.	Standardized interfaces, topology rules, and Dynamic Compliance.
Interoperability Risk	Independently developed infrastructure may become incompatible with regional systems.	Common architectural principles and defined stakeholder boundaries.
Architectural Drift Risk	Incremental infrastructure evolution may progressively erode the defining characteristics of the architecture.	Mandatory Dynamic Compliance preserving the applicable Architecture Class throughout its lifecycle.
Governance Risk	Multi-stakeholder infrastructure may evolve inconsistently over time.	Architecture governance and Real-Time Stewardship supporting continuous architectural alignment.

These architectural responses collectively preserve the defining characteristics of the applicable Architecture Class throughout the infrastructure lifecycle, enabling HOPT to function as a **Dynamically Preserved Architecture** whose long-term value is maintained as infrastructure evolves.

5. Purpose within HOPT-AS

HOPT-AS has been developed on the principle that **architecture itself constitutes a long-term infrastructure asset**.

The purpose of HOPT-AS is therefore not merely to define the Hub-Only Pipeline Topology, but to establish a family of **Dynamically Preserved Architectures** whose defining characteristics are continuously maintained through **Dynamic Compliance**.

By preserving architectural integrity throughout planning, deployment, operation, expansion, and long-term infrastructure evolution, HOPT-AS addresses **Architectural Risk**—a category of system-level risk that extends beyond the scope of conventional engineering, financial, legal, environmental, regulatory, and commercial assessments.

Accordingly, HOPT-AS complements traditional project due diligence by providing a structured architectural framework through which the long-term coherence, interoperability, scalability, and risk-mitigating characteristics of CCUS infrastructure are continuously preserved throughout the operational lifecycle of evolving infrastructure systems.

ARCHITECTURAL DRIFT AND DYNAMIC COMPLIANCE

(Informative — Non-Normative)

1. Architecture as a Risk Mitigation System

Every architecture exists because it mitigates one or more categories of system-level risk. The architectural principles embodied within a system are not arbitrary design choices; rather, they represent deliberate mechanisms for reducing complexity, improving scalability, protecting interoperability, and preventing undesirable system behaviors.

In the Hub-Only Pipeline Topology (HOPT), the architectural principles mitigate risks associated with fragmented infrastructure development, excessive pipeline proliferation, incompatible network expansion, inefficient hub deployment, permitting complexity, and long-term loss of scalability.

These risk-mitigating characteristics constitute the architectural integrity of HOPT.

1A. Open Architecture

The Hub-Only Pipeline Topology is an open architecture. Its architecture is intentionally designed to accommodate the continuous addition, removal, reassignment, and evolution of participating emitters, hubs, logistics pathways, and associated infrastructure without requiring reconstruction of the underlying hub-only pipeline topology. This adaptability is one of HOPT's principal advantages. However, the flexibility inherent in an open architecture also increases the risk of incremental decisions that, while locally beneficial, may collectively erode the defining characteristics of the architecture. HOPT-AS therefore requires Dynamic Compliance to ensure that operational flexibility remains consistent with the governing architectural principles of the Hub-Only Pipeline Topology.

2. Architectural Drift

Although an architecture may be fully compliant when first implemented, infrastructure rarely remains static.

CCUS systems evolve over decades through the addition of new emitters, regeneration hubs, logistics pathways, pipeline corridors, storage facilities, utilization projects, and independent infrastructure developments undertaken by multiple stakeholders.

Unlike conventional emitter-connected pipeline systems, HOPT is an open architecture in which emitter participation is enabled through flexible solids logistics rather than fixed pipeline connections. Emitters may be added, withdrawn, reassigned between hubs, or served through evolving logistics arrangements without altering the hub-only pipeline network. This

operational flexibility is a fundamental characteristic of HOPT and enables scalable participation by diverse industrial facilities.

Individual decisions that appear technically sound in isolation may collectively erode the architectural characteristics that originally justified adoption of the architecture.

HOPT-AS refers to this gradual loss of architectural integrity as **Architectural Drift**.

Architectural Drift may occur even where every individual project appears locally compliant.

Without coordinated architectural governance, Architectural Drift may result in:

- incompatible hub siting;
- fragmented logistics networks;
- conflicting pipeline corridors;
- duplicate aggregation infrastructure;
- reduced interoperability;
- constrained future backbone expansion; and
- loss of the architectural benefits originally intended by HOPT.

3. Dynamic Compliance

Because HOPT is an open architecture whose operational relationships evolve over time, compliance cannot be determined solely at the time of initial design or certification. HOPT-AS therefore establishes Dynamic Compliance as a mandatory architectural requirement for preserving the defining characteristics of the Hub-Only Pipeline Topology throughout the planning, deployment, operation, expansion, modification, and long-term evolution of CCUS infrastructure.

Dynamic Compliance is the continuous evaluation and preservation of the architectural integrity, governing principles, and risk-mitigating characteristics of HOPT as infrastructure evolves.

Every change affecting topology, emitter participation, hub assignment, logistics connectivity, infrastructure expansion, or other architecturally significant relationships shall preserve compliance with the governing principles of HOPT-AS. Compliance is therefore maintained continuously throughout the lifecycle of the architecture rather than verified only at discrete certification events.

4. Real-Time Stewardship

Real-Time Stewardship is the operational mechanism through which mandatory Dynamic Compliance is maintained.

Real-Time Stewardship continuously evaluates infrastructure evolution against the governing architectural principles of HOPT, enabling coordinated growth while preserving long-term architectural integrity.

The purpose of stewardship is not to control assets or engineering decisions, but to protect the architecture itself.

5. Purpose within HOPT-AS

The fundamental purpose of HOPT-AS is not only to define the Hub-Only Pipeline Topology, but also to ensure that its defining architectural characteristics remain continuously preserved throughout the lifecycle of an open and evolving CCUS infrastructure. Dynamic Compliance is therefore an inherent architectural requirement of HOPT-AS, ensuring that operational flexibility, phased deployment, and infrastructure expansion do not result in Architectural Drift or loss of architectural integrity.

This objective is achieved through governance, Dynamic Compliance, Real-Time Stewardship, and assurance mechanisms defined elsewhere in this Standard, which collectively preserve the architectural integrity, interoperability, and long-term resilience of the Hub-Only Pipeline Topology as infrastructure evolves.

DYNAMICALLY PRESERVED ARCHITECTURES

(Normative)

The Hub-Only Pipeline Topology Architecture Standard (HOPT-AS) establishes a family of Architecture Classes that collectively constitute the Hub-Only Pipeline Topology (HOPT). Every Architecture Class defined by HOPT-AS is, by definition, a **Dynamically Preserved Architecture (DPA)**.

A Dynamically Preserved Architecture is an Architecture Class whose defining architectural characteristics shall be continuously preserved throughout the operational life of the infrastructure system. The architectural value of a DPA derives not only from its initial design, but from the continued preservation of the structural characteristics through which it mitigates system-level risks, enables scalable infrastructure growth, maintains interoperability, and supports long-term operational and capital efficiency.

HOPT is an open architecture in which participating emitters, hubs, logistics pathways, and supporting infrastructure may evolve over time without altering the fundamental Hub-Only Pipeline Topology. This operational flexibility is an inherent characteristic of HOPT. However, because infrastructure systems continuously evolve, unmanaged change will inevitably result in Architectural Drift, progressively eroding the defining characteristics and risk-mitigating properties of the applicable Architecture Class.

Accordingly, every Architecture Class defined by HOPT-AS **shall be maintained through Dynamic Compliance**. Dynamic Compliance continuously evaluates infrastructure evolution against the defining architectural characteristics of the applicable Architecture Class and ensures that all architecturally significant changes preserve the integrity, identity, and intended risk-mitigation properties of that Architecture Class.

An implementation that is no longer maintained through Dynamic Compliance shall no longer be regarded as operating as a Dynamically Preserved Architecture, irrespective of whether its original design conformed to the applicable Architecture Class. Initial conformance alone is insufficient to preserve architectural status where subsequent infrastructure evolution results in Architectural Drift.

Dynamic Compliance is therefore an inherent and mandatory characteristic of every Dynamically Preserved Architecture defined by HOPT-AS. Together, the Architecture Classes established by this Standard and the Dynamic Compliance requirements governing their evolution ensure that HOPT remains a living architectural framework whose defining characteristics are continuously preserved throughout the lifecycle of evolving infrastructure systems.

REAL-TIME STEWARDSHIP AND DYNAMIC COMPLIANCE

(Informative — Non-Normative)

HOPT-AS establishes Dynamic Compliance as the mandatory mechanism for preserving the architectural integrity of the Hub-Only Pipeline Topology throughout the lifecycle of an evolving infrastructure system. Because HOPT is an open architecture in which emitters, hubs, logistics pathways, and supporting infrastructure may evolve over time, continuous oversight is required to ensure that such evolution preserves the defining characteristics of the applicable Architecture Class.

Real-Time Stewardship is the operational framework through which Dynamic Compliance is implemented. It continuously evaluates architecturally significant changes to ensure that infrastructure evolution remains consistent with the governing principles, system boundaries, topology rules, and permitted Architecture Classes defined by HOPT-AS.

The stewardship function is limited to architectural oversight. It preserves topology integrity and long-term interoperability without interfering with asset ownership, commercial relationships, engineering design, operational control, or regulatory responsibilities.

Together, Dynamic Compliance and Real-Time Stewardship enable HOPT to function as a living architectural framework, ensuring that operational flexibility and phased infrastructure expansion do not result in Architectural Drift or loss of the defining characteristics of the Hub-Only Pipeline Topology.

Detailed requirements governing Dynamic Compliance, Real-Time Stewardship, and their application are defined in the normative provisions of this Standard.

RELEVANCE OF DYNAMIC COMPLIANCE TO MRV AND CHAIN OF CUSTODY

The Hub-Only Pipeline Topology intentionally decouples emitters from the common pipeline network by requiring CO₂ to enter the transportation system through Regeneration Hubs rather than through direct pipeline connections. This architectural approach provides significant benefits in scalability, flexibility, and system-level risk mitigation. However, because physical connectivity alone no longer establishes the origin or legitimacy of CO₂ entering the network, Dynamic Compliance acts as a fundamental architectural assurance mechanism.

Dynamic Compliance continuously verifies that architecturally significant decisions, infrastructure changes, and CO₂ entering and exiting the HOPT network remain consistent with the architectural boundaries, stakeholder relationships, and functional assumptions established by the applicable Architecture Class.

It thereby preserves the system-level risk mitigation characteristics embodied within HOPT-AS and supports the integrity of the MRV and Chain of Custody framework.

READER'S GUIDE — STRUCTURE AND USE OF THIS STANDARD

(Informative — Non-Normative)

This document contains both normative and informative material.

Normative sections establish the mandatory architectural principles, requirements, constraints, system boundaries, stakeholder responsibilities, Architecture Classes, and Dynamic Compliance obligations that define conformance with the Hub-Only Pipeline Topology Architecture Standard (HOPT-AS).

Informative sections provide explanatory context, architectural rationale, background, implementation guidance, and the conceptual foundations supporting the normative requirements. Informative material is intended to aid understanding and implementation and does not, by itself, establish compliance with this Standard.

HOPT-AS should be read as an **architecture preservation standard** as well as an architecture definition standard. The early sections explain the principles and characteristics of the Hub-Only Pipeline Topology, while the subsequent normative sections define the Architecture Classes and the Dynamic Compliance requirements through which those architectural characteristics are continuously preserved as infrastructure evolves.

The Standard is organized to guide the reader through the logical development of the HOPT framework:

- The introductory sections explain the purpose, scope, and architectural concepts underlying the Hub-Only Pipeline Topology.
- The foundational principles establish the mandatory characteristics that define HOPT.
- The stakeholder, system boundary, and topology sections define the permissible structure and operation of HOPT implementations.
- The Dynamic Compliance provisions establish how the defining characteristics of each Architecture Class are continuously preserved throughout the infrastructure lifecycle.
- The remaining normative sections define the detailed requirements applicable to the implementation, evolution, and governance of HOPT systems.

Readers seeking to understand the architectural concepts should begin with the informative sections before progressing to the normative requirements. Readers implementing or assessing HOPT systems should apply the normative provisions in their entirety, recognizing that conformance depends not only on initial implementation but also on maintaining Dynamic Compliance throughout the operational life of the infrastructure.

Section headings explicitly identify whether material is **Normative** or **Informative**.

In the event of ambiguity, conflict, or questions regarding the interpretation or application of this Standard, formal interpretations issued in writing by Novonanmek Material Sciences Private Limited, as owner and governing authority of HOPT-AS, shall prevail for the purposes of conformity claims and official interpretation of the Standard. Independent technical analysis or engineering judgment may support implementation but does not constitute an authoritative interpretation of HOPT-AS.

The "**How to Use This Standard**" section that follows provides practical guidance for applying HOPT-AS in project planning, infrastructure development, and long-term operation.

HOW TO USE THIS STANDARD

(Informative — Non-Normative)

1. Purpose of This Guide

This section explains **how stakeholders should use the Hub-Only Pipeline Topology Architecture Standard (HOPT-AS) in practice.**

HOPT-AS is a system-level architecture and governance standard for open CCUS infrastructure. It not only defines the architectural principles, system boundaries, and topology requirements of the Hub-Only Pipeline Topology (HOPT), but also establishes the Dynamic Compliance requirements through which those defining architectural characteristics are continuously preserved as infrastructure evolves. HOPT-AS should therefore be applied throughout the lifecycle of a HOPT implementation rather than solely during its initial planning or design.

This guide clarifies:

- What decisions this Standard is intended to inform
- What decisions are intentionally left to implementers
- How different stakeholders should apply HOPT-AS in real projects

2. What HOPT-AS Tells You to Do

HOPT-AS provides **clear, mandatory direction** on the following:

2.1 Architectural Topology

HOPT-AS defines:

- Where CO₂ may be handled in gaseous form
- Where CO₂ must remain in solid-bound form
- Which nodes may connect to pipelines
- Which nodes are explicitly prohibited from pipeline connection

These rules are **non-negotiable** for any system claiming alignment with HOPT-AS.

2.2 System Boundaries and Interfaces

The Standard defines:

- Distinct system domains (Emitter, Logistics, Hub, Pipeline, Storage)
- Allowed and forbidden interfaces between domains
- Clear hand-off points between stakeholders

This enables multiple independent parties to design and operate their systems without architectural conflict.

2.3 Allowed Configurations

HOPT-AS defines a **limited set of permitted topology classes** and scaling pathways. Implementers must select one of these classes and design within its constraints.

2.4 Stakeholder Responsibilities

For each participant category, HOPT-AS specifies:

- Core responsibilities
- Required interfaces
- Prohibited actions

This prevents overlap, ambiguity, and uncontrolled architectural drift.

3. What HOPT-AS Does Not Specify

HOPT-AS intentionally does **not** prescribe:

- Detailed capture chemistry or reactor design
- Sorbent formulation or regeneration kinetics
- Pipeline diameter, metallurgy, or routing
- EPC construction methods
- Site-specific safety case design
- Storage reservoir engineering or injection strategies

These matters are expected to be addressed by:

- Qualified EPC contractors
- Technology vendors
- Storage operators
- Regulators
- Project-specific engineering studies

HOPT-AS defines the architectural requirements, governing principles, and Dynamic Compliance obligations necessary for implementing the Hub-Only Pipeline Topology. The Standard intentionally does not prescribe detailed engineering methodologies, project execution procedures, optimization techniques, or operational practices, which remain the responsibility of implementers, provided that such activities preserve compliance with the applicable Architecture Class and maintain Dynamic Compliance throughout the operational lifecycle of the infrastructure system.

3.1 Dynamic Compliance

HOPT-AS defines the architecture and the requirements necessary to preserve that architecture throughout its operational lifecycle. Accordingly, implementation of HOPT-AS is not complete upon initial deployment. Implementers shall maintain Dynamic Compliance as infrastructure evolves, ensuring that changes affecting topology, hub participation, emitter relationships, logistics pathways, and other architecturally significant characteristics remain consistent with the applicable Architecture Class.

4. How Different Stakeholders Should Use This Standard

4.1 Emitters

Emitters should use HOPT-AS to:

- Confirm eligibility to participate
- Understand required capture mode (solid-looping)
- Understand prohibited activities (pipelines, compression, regeneration)
- Design their facilities to interface only via solids logistics

4.2 Hub Developers and EPCs

Hub developers should use HOPT-AS to:

- Select an appropriate topology class
- Determine hub responsibilities and boundaries
- Design regeneration, compression, and interface systems
- Ensure no emitter-side pipeline connectivity is introduced
- Plan scalable expansion consistent with permitted classes

4.3 Pipeline Operators

Pipeline operators should use HOPT-AS to:

- Design hub-to-hub pipeline systems only
- Confirm prohibited connections and routing
- Align pipeline operations with hub injection/withdrawal rules

4.4 Logistics Providers

Logistics providers should use HOPT-AS to:

- Define solids-only transport operations
- Implement chain-of-custody tracking
- Ensure no gaseous CO₂ handling occurs within logistics systems

4.5 Storage and Utilization Operators

Storage and utilization operators should use HOPT-AS to:

- Confirm downstream-only participation
- Accept only pipeline-grade CO₂ from certified hubs
- Align MRV systems with HOPT registry requirements

4.6 Regulators and Financiers

Regulators and financiers should use HOPT-AS as:

- A reference architecture for evaluating proposals
- A basis for assessing system coherence and scalability
- An assurance framework for multi-stakeholder coordination

5. How to “Build” a HOPT System Using This Standard

In practice, implementing a HOPT system involves:

1. Selecting the appropriate Architecture Class.
2. Assigning stakeholder roles and responsibilities.
3. Respecting all mandatory system boundaries and topology rules.
4. Designing engineering solutions within those architectural constraints.
5. Implementing infrastructure in accordance with the selected Architecture Class.
6. Maintaining Dynamic Compliance throughout the operational lifecycle as infrastructure evolves.

HOPT-AS ensures that independently designed components integrate into a **coherent, scalable, and governable system**.

6. Summary

HOPT-AS should be read and applied as a **rules-based architectural framework**

It provides:

- Clear direction on *what must be built*
- Clear limits on *what must not be built*
- Clear guidance on *how systems may grow*

Detailed engineering, construction, and operational design are expected to occur **within** this framework, not outside it.

Accordingly, implementation of HOPT-AS is not complete upon initial deployment. Conformance with this Standard requires both initial implementation in accordance with the

applicable Architecture Class and the continued preservation of that Architecture Class through Dynamic Compliance as the infrastructure evolves.

Normative Sections

SECTION 1 — INTRODUCTION & PURPOSE

(Normative)

1.1 Context

Large-scale deployment of carbon capture, utilization, and storage (CCUS) is constrained worldwide by the cost and complexity of transporting CO₂ from thousands of emitters to a limited number of storage or utilization sites. In conventional architectures, each emitter must connect to a CO₂ pipeline network through dedicated tie-ins, onsite compression, and gas-handling systems. This model is difficult to scale in regions with:

- Limited existing pipeline infrastructure,
- Dense or contested land-use,
- Complex, multi-agency permitting, and
- A large number of small and mid-size emitters.

India and many emerging economies face exactly these conditions: dispersed industrial clusters, minimal gas pipeline legacy, and high barriers for permitting linear infrastructure across multiple states. Building an emitter-to-storage CO₂ pipeline grid under such constraints would require decades and very high capital expenditure.

At the same time, solid-looping capture technologies—such as Calcium Looping and related oxide cycles—enable CO₂ to be captured at emitters in **solid-bound form**, transported as solids using ordinary logistics, and regenerated at centralized facilities.

Thus, if CO₂ is released only at centralized regeneration hubs, **pipelines are needed only between hubs, not at emitters**.

This insight—the relocation of gaseous CO₂ handling from emitters to hubs—enables a new topology: the **Hub-Only Pipeline Topology (HOPT)**. In this topology, emitters participate through solids logistics; only hubs are connected by CO₂ pipelines.

However, moving from conceptual topology to **real deployment** requires more than a technology description. It requires a **governed architecture standard** defining:

- Roles and responsibilities of hubs, emitters, pipeline operators, logistics providers, and storage operators,
- System boundaries and allowed configurations,
- Participation and compliance conditions,
- Registry and certification rules, and
- A consistent framework for scaling HOPT across regions and countries.

The Hub-Only Pipeline Topology Architecture Standard (HOPT-AS) is created to provide that structure.

1.2 Purpose of HOPT-AS

The purpose of HOPT-AS is to establish a standardized, rules-based, multi-stakeholder framework for designing, deploying, and governing CCUS systems based on the Hub-Only Pipeline Topology (HOPT).

Specifically, HOPT-AS exists to:

a. **Define the core topology and its non-negotiable properties**

HOPT-AS codifies the hub-only pipeline principle: **emitters are excluded from CO₂ pipeline connections; only hubs inject into and withdraw from the gaseous CO₂ pipeline network.**

b. **Establish clear system boundaries**

It sets boundaries between:

- Emitter sites and their capture systems,
- Regeneration hubs,
- CO₂ pipeline network,
- Storage or utilization sites, and
- Logistics systems that move solids between emitters and hubs.

c. **Create a common language for stakeholders**

HOPT-AS introduces standardized terms and categories for:

- Hub types and capacities,
- Emitter participation classes,
- Solids logistics configurations,
- Pipeline connectivity patterns,
- Storage integration modes, and
- Governance and registry status

d. **Enable hub developers and EPCs to make structured, defensible design choices**

HOPT-AS provides a limited, pre-defined set of topology families and deployment models from which hub developers, EPCs, and system integrators must choose, rather than creating bespoke architectures for each region or cluster.

e. **Ensure emitters can participate without pipeline-side burden**

HOPT-AS formalizes the condition that emitters do not require thereby lowering their entry barriers and standardizing the way they connect to HOPT hubs.

- Pipeline tie-ins,
- Onsite CO₂ compression, or
- Regeneration facilities

f. **Provide regulators and policymakers with a reference framework**

It offers a coherent architectural template for:

- Evaluating hub projects,
- Structuring CCUS-as-a-Service models,
- Coordinating land-use and permitting, and
- Aligning HOPT deployment with national CCUS missions.

g. **Enable scalable, repeatable deployment across regions**

HOPT-AS is designed to be replicable across multiple industrial clusters, states, or countries, so that each new hub system does not require reinvention of the underlying architecture.

1.3 What HOPT-AS Is?

HOPT-AS is a **system-level architecture and governance standard** for CCUS built around the Hub-Only Pipeline Topology.

It consists of:

- Foundational principles,
- Mandatory rules and constraints,
- Hub, emitter, and pipeline topology classes,
- Stakeholder roles and domain boundaries,
- Participation and certification conditions,
- Registry and compliance structures, and
- Informative guidance for deployment and scaling.

HOPT-AS defines **how** HOPT-based systems are structured and governed—it does **not** prescribe detailed engineering design.

1.4 What HOPT-AS Is Not?

HOPT-AS deliberately avoids:

- Specifying capture chemistry in detail (e.g., exact Ca-looping process design),
- Prescribing the design of kilns, regenerators, or reactors,
- Dictating pipeline diameter, wall thickness, or route alignment,
- Specifying storage-site selection or geomechanical criteria,
- Acting as an MRV (Measurement, Reporting, Verification) methodology by itself,
- Replacing detailed EPC engineering, safety studies, or regulatory submissions.

HOPT-AS **sets the architecture and governance boundaries** within which these technical and regulatory activities are carried out.

1.5 Scope of Application

HOPT-AS applies to:

- CCUS systems that use **solid-looping capture** at emitters and centralized regeneration at hubs,
- Pipeline networks in which only hubs are connected by gaseous CO₂ pipelines,
- Logistics chains that move CO₂-laden solids between emitters and hubs,
- Clusters of emitters linked to one or more hubs (Such emitters may be distributed across multiple industrial facilities or may comprise multiple emitting sites located within a single industrial facility or industrial campus), and
- Regional or national networks of hubs connected by pipelines.

It does **not** apply to:

- Conventional emitter-to-storage pipeline systems where emitters inject CO₂ directly into pipelines,
- Purely solvent-based capture systems without solid-looping,
- Projects that do not implement the hub-only pipeline principle.

1.6 Multi-Stakeholder Orientation

Deployment of the Hub-Only Pipeline Topology is inherently multi-stakeholder. HOPT-AS is designed to coordinate the interaction of:

- Emitters
- Hub Developers / Hub Operators
- Pipeline Operators
- Solids Logistics Providers
- Storage / Utilization Operators
- Capture Technology Vendors
- Novonanmek Material Sciences Private Limited, as Owner and Governing Authority of this Standard (Novonanmek)

By defining clear domains, interfaces, and responsibilities for each participant category, HOPT-AS prevents overlap, ambiguity, and architectural fragmentation while enabling scalable deployment.

1.7 Normative vs. Informative Components

HOPT-AS contains both:

Normative (Mandatory) Components:

- Core HOPT topology rules,

- Hub-only pipeline constraints,
- Eligibility and participation requirements,
- Classification of hub and emitter types,
- Registry, certification, and compliance requirements,
- Permitted topology families and connection patterns.

Informative (Guidance) Components:

- Background explanations and rationale,
- Examples of deployment models,
- Indicative economic and scaling behavior,
- Best-practice recommendations,
- Illustrative case studies and diagrams.

This structure ensures that the standard is both actionable and understandable.

1.8 Authority and Updates

HOPT-AS is owned and stewarded by Novonanmek Material Sciences Private Limited as its originator and official steward

Novonanmek is the originator, owner and steward of this standard responsible for:

- Maintaining the authoritative version of this Standard
- Issuing revisions, updates, and clarifications
- Managing certification, registry, and compliance frameworks
- Approving exceptions or controlled deviations
- Aligning the Standard with evolving regulatory and market contexts

No other entity may issue interpretations, certifications, or official guidance under the HOPT-AS name.

1.9 How HOPT-AS Will Be Used

Stakeholders use HOPT-AS in the following ways:

- **Emitters:** To understand eligibility, participation models, solids logistics and interface expectations with hubs.
- **Hub Developers:** To design hub capacity, clustering logic, solids flows, and hub-to-hub pipeline integration.
- **Pipeline Operators:** To structure hub-only connectivity consistent with HOPT rules.
- **Logistics Providers:** To align solids transport operations with topology and governance requirements.
- **Storage Operators:** To integrate storage services coherently into hub-based networks.

- **Policy Makers and Regulators:** To assess proposals and design enabling frameworks for HOPT deployment.
- **Novonanmek:** To certify projects, manage registry entries, and ensure consistent interpretation.

1.10 Summary

HOPT-AS provides a structured, rules-based, and stakeholder-aligned architecture for deploying the Hub-Only Pipeline Topology at scale. It transforms what could otherwise be a set of bespoke, uncoordinated CCUS projects into a **governed, repeatable, and interoperable framework** for national and regional carbon management.

SECTION 2 — FOUNDATIONAL PRINCIPLES OF HOPT-AS

(Normative)

The Hub-Only Pipeline Topology Architecture Standard (HOPT-AS) is built on a set of **non-negotiable, foundational principles**. These principles establish the architectural identity of HOPT, constrain permissible configurations, define stakeholder domains, and ensure that all deployments across regions, industries, and hub systems follow a consistent structural logic.

These principles **must be satisfied** for a system to be considered HOPT-compliant.

2.1 Principle 1 — Emitters Are Excluded From the CO₂ Pipeline Network

The defining characteristic of HOPT is that **emitters do not connect to CO₂ pipelines**.

2.1.1 Mandatory Conditions

- No emitter may inject, vent, extract, or process gaseous CO₂ into/from pipelines.
- Emitters may not install:
 - Pipeline tie-in valves,
 - Onsite CO₂ compression equipment for pipeline service,
 - Pressure control facilities intended for pipeline-grade CO₂.

2.1.2 Rationale

This principle is rooted in the core insight of the patented configuration: *gaseous CO₂ handling is **centralized** not distributed*.

This:

- Removes pipeline safety and permitting burdens from emitters,
- Enables emitters of any size to participate,
- Avoids distributed pipeline routing constraints,
- Makes HOPT scalable across dense industrial clusters.

This is the cornerstone of the entire topology.

For the purposes of HOPT-AS, emitter participation may occur through:

- geographically distributed industrial facilities,
- multiple emitter nodes within a single industrial facility,
- or combinations thereof,

provided that all emitter nodes remain excluded from direct gaseous CO₂ pipeline interaction.

2.2 Principle 2 — CO₂ Pipelines Connect Hubs Only (Hub–Hub Topology)

HOPT-AS requires that **the gaseous-phase CO₂ pipeline network is exclusively a hub-to-hub system.**

2.2.1 Mandatory Conditions

- Only hubs may connect to CO₂ pipelines.
- Pipelines shall not branch, terminate, or originate at emitter sites.
- All pipeline injection points and extraction points must be located at hubs.

2.2.2 Rationale

Centralized handling of gaseous CO₂:

- Simplifies permitting,
- Reduces risk concentration,
- Enables higher pipeline utilization,
- Allows hub-level balancing and network control.

This principle transforms CCUS from a distributed model to a **central-node network**.

2.3 Principle 3 — Emitters Participate Only Through Solids-Based Logistics

Emitters shall interface with HOPT exclusively via solids logistics, including but not limited to road, rail, barge, conveyor, pneumatic transfer, internal industrial transport systems, or equivalent solids-handling mechanisms.

2.3.1 Mandatory Conditions

- Emitters shall interface with HOPT exclusively via **solids logistics** (road, rail, barge, conveyor, etc.).
- Emitters must not produce pipeline-ready CO₂.
- The emitter–hub interface is a **logistics interface**, not a pipeline or gaseous interface.

2.3.2 Rationale

This principle:

- Enables small and mid-sized emitters to join without capital-intensive gas handling,
- Decouples emitters from permitting-sensitive pipeline infrastructure,
- Allows hubs to scale independently from the number of emitters,
- Makes CCUS as-a-service commercially viable.

Solids logistics is the **unifying bridge** between emitters and hubs.

2.4 Principle 4 — CO₂ Regeneration and Compression Occur Only at Hubs

All gaseous CO₂ formation, concentration, conditioning, and compression must be performed within hubs—not at emitters.

2.4.1 Mandatory Conditions

- Regeneration (CO₂ release from solids) is a **hub operation only**.
- Gas-phase CO₂ must be pipeline-specification before entering any pipeline.
- Emitters must not regenerate CO₂ locally for pipeline purposes (unless operating outside HOPT).

2.4.2 Rationale

Centralizing regeneration:

- Consolidates safety risk,
- Optimizes equipment utilization,
- Simplifies local permitting at emitters,
- Allows hubs to operate continuous, high-throughput regeneration systems,
- Ensures pipeline consistency.

This is fundamental to the HOPT identity.

2.5 Principle 5 — Distinct and Non-Overlapping Stakeholder Domains

HOPT requires **strict separation of responsibilities**:

- Emitters handle capture + storage of loaded solids onsite.
- Logistics Providers transport solid carbon carriers.
- Hubs regenerate CO₂ and manage sorbent cycling.
- Pipeline Operators manage hub-to-hub CO₂ flow.
- Storage Operators inject CO₂ underground or use industrial sinks.

2.5.1 Mandatory Conditions

Each role has clearly defined:

- Boundaries of activity;
- Interface responsibilities;
- Data-sharing obligations;
- Commercial and regulatory obligations;
- Safety and compliance domains.

2.5.2 Rationale

To prevent fragmentation, conflict, and scope overlap, HOPT-AS enforces strict domain clarity.

This ensures:

- Interoperability among stakeholders,
- Predictable interfaces,
- Scalable deployment across regions.

2.6 Principle 6 — Standardized Hub Classes and Capacities

Hubs must be classified into **internally consistent classes**, based on:

- Regeneration capacity,
- Pipeline interfacing capacity,
- Solids throughput,
- Storage handling limits,
- Number of supported emitters.

2.6.1 Mandatory Conditions

- Each hub must be mapped to an approved HOPT-AS hub class.
- Hub classes dictate permissible connections, capacity ranges, and topology families.

2.6.2 Rationale

Hub classes allow:

- Regional planning,
- Predictable scaling,
- Compatibility between hubs and emitters,
- A structured market for hub developers.

Hub classifications prevent arbitrary, un-scalable designs.

2.7 Principle 7 — Governance by the Standard Owner

The HOPT system is governed, interpreted, certified, and updated exclusively by **Novonanmek Material Sciences Private Limited**.

2.7.1 Mandatory Conditions

- Only Novonanmek may issue formal interpretations or clarifications
- All certified participants must be registered under Novonanmek-administered systems
- Unauthorized architectural variants are not permitted

2.7.2 Rationale

HOPT involves many independent actors operating across logistics, pipelines, storage, and capture domains. Without centralized governance:

- Topology would fragment
- Compatibility would erode
- MRV integrity would fail
- Safety and regulatory consistency would be lost

Centralized governance by the Standard owner is therefore essential.

2.8 Principle 8 — HOPT-AS Defines Topology, Not Technology

HOPT-AS governs **how systems interconnect**, not the chemistry or physics of specific capture processes.

2.8.1 Mandatory Conditions

- HOPT-AS shall remain technology-neutral.
- It shall not prescribe sorbent formulations or reactor design.
- Vendors must adapt technology to the topology, not vice versa.

2.8.2 Rationale

Future-proofing:

- Allows the standard to outlive specific capture technologies,
- Supports innovation while preserving architecture,
- Ensures wide vendor participation.

This mirrors how HOPT remains technology-neutral.

2.9 Principle 9 — Scale Through Replicability and Modularity

HOPT-AS is designed for many hubs, not one.

2.9.1 Mandatory Conditions

- Hub systems must be modular.
- Topology families must be repeatable.
- Deployment must allow multiple clusters and regional expansion.

2.9.2 Rationale

National-scale decarbonization demands:

- Many hubs,
- Hundreds of emitters,
- Coordinated pipelines,
- Predictable scaling rules.

HOPT's topology must be replicable, not bespoke.

2.10 Principle 10 — Mandatory Compatibility across HOPT Systems

Systems deployed under HOPT-AS must be compatible with:

- Each other,
- Future expansions,
- Regional and national plans.

2.10.1 Mandatory Conditions

- Hub interconnections must use approved topology families.
- Solids logistics must follow compatible classification rules.
- Pipeline systems must interoperate with other hubs.

2.10.2 Rationale

This ensures that:

- Clusters do not become isolated silos,
- National CO₂ management systems can form,
- Regulatory and MRV systems remain aligned,
- Economies of scale emerge.

SECTION 3 — STAKEHOLDER MODEL AND DOMAIN RESPONSIBILITIES

(Normative)

HOPT-AS establishes a **multi-stakeholder architecture with clearly separated domains**, each with specific responsibilities and prohibited actions. These defined roles ensure interoperability, system-level coherence, and safe deployment of the Hub-Only Pipeline Topology.

The stakeholder model is normative.
Compliance with these boundaries is required for HOPT certification.

3.1 Overview of HOPT Stakeholder Categories

HOPT-AS defines the following primary stakeholder categories:

1. **Emitters**
2. **Hub Developers / Hub Operators (HD/HO)**
3. **Pipeline Operators (PO)**
4. **Solids Logistics Providers (SLP)**
5. **Storage & Utilization Operators (SUO)**
6. **Capture Technology Vendors (CTV)**

Each stakeholder type has discrete, non-overlapping responsibilities and interface boundaries.

3.2 Emitters (E)

Industrial facilities, process units, or localized emission systems where CO₂ is captured in solid-bound form and transferred into the HOPT architecture.

3.2.1 Core Responsibilities

Emitters are responsible for:

- Installing and operating capture systems that function as continuous or cyclic material loops and convert CO₂ into stable, transportable solid carbonates compatible with centralized regeneration,
- Ensuring capture-grade operation meeting hub loading specifications,
- Ensuring compatibility of capture systems with direct processing of industrial flue gas streams and, where feasible, integrating the handling of acid gases within the same process system,
- Deploying calcium-based alkaline systems, in widely implementable configurations, using aqueous or slurry-phase processes compatible with standard industrial gas-

cleaning equipment, with optional alkaline enhancement to improve performance under ambient or near-ambient conditions,

- Producing CO₂-laden solids meeting hub logistics and chemistry requirements,
- Storing material onsite pending transport,
- Receiving regenerated solids from hubs and integrating them into capture processes,
- Maintaining safe onsite handling of solid materials,
- Providing operational data required for MRV programs.

Such systems include solid-looping approaches such as calcium looping and related or modified variants, as well as other implementations that satisfy the functional and material requirements defined above.

3.2.2 Interface Responsibilities

Emitters must:

- Interface with hubs exclusively via solids logistics,
- Coordinate solids loading and unloading schedules with Solids Logistics Providers,
- Maintain traceability of material using HOPT-approved tagging systems,
- Follow chain-of-custody documentation for carbon accounting,
- Ensure delivered solids are chemically stable, non-hazardous, and consistent with alkaline earth carbonate-based regeneration requirements at hubs,
- Ensure supplied solids meet defined physical and chemical specifications, including particle stability, moisture tolerance, and handling characteristics required for safe transport and repeatable regeneration performance.

3.2.3 Prohibited Actions

Emitters may not:

- Inject CO₂ into pipelines,
- Regenerate CO₂ onsite for pipeline use,
- Connect to pipeline infrastructure,
- Handle pipeline-grade gaseous CO₂,
- Modify or bypassing solids logistics specifications,
- Perform functions reserved for hubs or pipeline operators,
- Deploy capture systems requiring upstream deep removal of flue gas contaminants as a prerequisite for CO₂ capture, where integrated processing is technically feasible,
- Deploy capture systems relying on continuous export, compression, or handling of gaseous CO₂ outside the emitter boundary.

These prohibitions reflect HOPT's foundational requirement that emitters are pipeline-excluded nodes.

3.3 Hub Developers / Hub Operators (HD/HO)

Entities that develop, own, and/or operate HOPT regeneration hubs.

3.3.1 Core Responsibilities

Hub Developers / Operators are responsible for:

- Designing, constructing, and operating regeneration hubs,
- Receiving CO₂-laden solids from multiple emitters,
- Regenerating gaseous CO₂,
- Conditioning and compressing CO₂ to pipeline specifications,
- Ensuring continuous sorbent loop cycling operations,
- Managing hub-wide heat/mass balances and throughput,
- Complying with pipeline operating constraints,
- Providing CCUS-as-a-Service commercially.

3.3.2 Interface Responsibilities

Hubs must interface with:

- **Emitters:** via solids intake and outbound regenerated solids,
- **Pipeline Operators:** at hub injection/withdrawal points,
- **Storage Operators:** through pipeline-controlled flows or downstream allocation,
- **Regulators:** for hub safety, environmental, and CO₂ accounting compliance.

3.3.3 Prohibited Actions

Hubs may **not**:

- Impose technology-specific requirements inconsistent with HOPT-AS,
- Allow emitters to connect to pipelines through hub-side bypasses,
- Alter topology families without formal written approval from Novonanmek,
- Perform pipeline operations (unless certified as integrated Hub–PO),
- Mix incompatible solids streams in violation of classification rules.

3.4 Pipeline Operators (PO)

Entities that design and operate **hub-to-hub CO₂ pipeline systems**.

3.4.1 Core Responsibilities

Pipeline Operators must:

- Design, construct, operate, and maintain gaseous CO₂ pipelines that connect hubs,
- Control injection, withdrawal, and flow balancing,

- Ensure pipeline-grade CO₂ specifications are met,
- Manage network contingencies and pressure-control strategies,
- Maintain regulatory compliance for pipeline safety.

3.4.2 Interface Responsibilities

Pipeline Operators interface with:

- **Hubs only**, not emitters,
- Storage Operators for final delivery or distribution,
- National/state permitting authorities,
- Hub Developers during design of connection points.

3.4.3 Prohibited Actions

Pipeline Operators may **not**:

- Route pipelines to emitter sites,
- Accept CO₂ from any non-hub source,
- Allow non-hub injection (no “unauthorized tap-ins”),
- Alter the topology to add emitter-side pipes.

These constraints preserve system integrity and are enforced by Novonanmek.

3.5 Solids Logistics Providers (SLP)

Operators of logistical systems for transporting solid carbon carriers

3.5.1 Core Responsibilities

SLPs must:

- Transport CO₂-laden solids from emitters to hubs,
- Transport regenerated solids from hubs to emitters,
- Maintain material traceability according to HOPT Registry requirements,
- Ensure safe handling and containment throughout transport,
- Comply with capacity and scheduling commitments.

3.5.2 Interface Responsibilities

SLPs interface with:

- Emitters,
- Hubs,
- Regional logistics networks (rail, road, barge, etc.),
- Novonanmek’s systems for chain-of-custody data.

3.5.3 Prohibited Actions

SLPs may **not**:

- Modify solids chemistry or specification,
- Handle gaseous CO₂,
- Act as intermediaries for CO₂ pipeline injection.

Their domain is **logistics only**, not processing or gas-handling.

3.6 Storage & Utilization Operators (SUO)

Entities responsible for the **final disposition of pipeline-grade CO₂** within the HOPT system

Storage & Utilization Operators (SUO) receive CO₂ exclusively from the HOPT Pipeline System and are responsible for either permanent storage or approved utilization pathways. SUOs operate strictly downstream of hubs and do not interact directly with emitters or solids logistics systems.

For governance and accounting purposes, SUOs are classified into two sub-categories:

- **SUO-S — Storage Operators** (permanent geological storage)
- **SUO-U — Utilization Operators** (industrial or commercial use of CO₂)

Both sub-categories are subject to HOPT system boundary rules and certification requirements, with additional obligations defined below.

3.6.1 Core Responsibilities

All SUOs must:

- Receive **pipeline-grade CO₂** exclusively via certified Pipeline Operators from HOPT-certified hubs;
- Accept CO₂ only at designated pipeline delivery points;
- Operate facilities in compliance with applicable safety, environmental, and regulatory requirements;
- Maintain full **MRV (Measurement, Reporting, and Verification)** compliance as required by Novonanmek;
- Ensure accurate reporting of CO₂ volumes, timing, and disposition outcomes into the HOPT Registry.

Additional responsibilities by sub-classification:

SUO-S (Storage Operators) must additionally:

- Inject CO₂ into approved geological formations intended for permanent storage;

- Maintain long-term containment integrity and monitoring programs;
- Comply with storage-specific MRV, post-injection monitoring, and liability frameworks.

SUO-U (Utilization Operators) must additionally:

- Operate utilization pathways that meet applicable regulatory acceptance criteria;
- Declare the **carbon fate classification** of the utilization pathway (e.g. Permanent, delayed re-emission, cyclical);
- Comply with utilization-specific lifecycle MRV requirements, including any re-emission or downstream responsibility obligations;
- Ensure transparency regarding the permanence or non-permanence of CO₂ outcomes.

3.6.2 Interface Responsibilities

SUOs may interface only with the following entities:

- **Pipeline Operators (primary interface)** — for receipt of pipeline-grade CO₂;
- **Hub Operators** — for volume forecasting, scheduling, and operational coordination;
- **Novonanmek** — for certification, registry participation, MRV reporting, and compliance audits;
- **Regulatory authorities** — as required by law for storage or utilization activities.

SUOs shall not interface directly with emitters or solids logistics systems.

3.6.3 Prohibited Actions

SUOs may not:

- Receive CO₂ directly from emitters, capture systems, or solids logistics providers;
- Accept CO₂ that does not meet pipeline-grade specifications;
- Bypass or circumvent the HOPT Pipeline System;
- Regenerate CO₂ from solids or handle CO₂ in solid-bound form;
- Operate pipeline segments unless separately certified as an approved dual-role entity;
- Misrepresent utilization outcomes as permanent storage.

3.6.4 Topology Enforcement Statement

The HOPT topology enforces a clean and non-negotiable chain:

Emitter → Hub → Pipeline → Storage / Utilization

Any deviation from this chain constitutes a violation of HOPT-AS and is grounds for suspension or decertification.

3.7 Capture Technology Vendors (CTV)

Technology providers for capture systems

3.7.1 Core Responsibilities

CTV responsibilities include:

- Designing and supplying solid-looping capture units suitable for HOPT integration,
- Ensuring technology meets HOPT material compatibility standards,
- Providing technical documentation for emitter-hub integration,
- Supporting MRV traceability at the material level.

3.7.2 Interface Responsibilities

CTV interfaces with:

- Emitters (primary technology users),
- Hub Developers (for regeneration compatibility),
- Novonanmek (for certifying technology families or variants),
- EPC/Integrator firms (for system integration).

3.7.3 Prohibited Actions

CTVs may **not**:

- Unilaterally redefine hub/emitter boundaries,
- Create topology variations outside HOPT-AS,
- Classify proprietary variants as HOPT-AS-compliant without formal written approval from Novonanmek

SECTION 4 — SYSTEM BOUNDARIES & DOMAIN INTERFACES

(Normative)

HOPT-AS defines explicit and non-overlapping **system boundaries** between stakeholder domains. These boundaries are mandatory and exist to maintain safety, interoperability, scalability, and architectural coherence across all HOPT deployments.

System boundaries are normative:

A configuration that violates any boundary defined in this section is NOT HOPT-compliant.

4.1 Overview of Boundary Structure

The HOPT architecture consists of five primary physical and functional systems:

1. **Emitter System (ES)** – capture + solids handling at emitter
2. **Solids Logistics System (SLS)** – transport of solids
3. **Hub System (HS)** – regeneration + sorbent cycling + pipeline interfacing
4. **Pipeline System (PS)** – hub-to-hub CO₂ movement
5. **Storage & Utilization System (SUS)** – final disposition of CO₂

Each system has:

- **A written definition**
- **A domain boundary**
- **Allowed interfaces**
- **Forbidden interfaces**
- **Responsibility coverage**

These must be respected in all HOPT deployments.

4.2 Boundary 1 — Emitter System (ES) Boundary

The **Emitter System boundary** encloses all activities required to:

- Capture CO₂ in solid-bound form,
- Store loaded solids onsite,
- Receive regenerated solids from the hub,
- Interface with logistics for outward/inward movement.

4.2.1 What Lies Inside This Boundary

- Solid-looping capture reactors

- Solids loading/unloading stations
- Short-term solids storage silos
- Emitter-side material traceability systems
- Emitter-side MRV instrumentation
- Emitter operational controls

4.2.2 Allowed Interfaces

Emitters may interface only with:

1. **Solids Logistics System (SLS)**
 - Outbound: CO₂-rich solids → hub
 - Inbound: regenerated solids → emitter
2. **HOPT Registry (digital)**
 - Uploading emitter participation data
 - Recording chain-of-custody inputs

4.2.3 Prohibited Interfaces

Emitters may **not** interface with:

- **Pipeline System (PS)** — no tie-ins, no taps
- **Storage System (SUS)** — no direct deliveries
- **Hub System (HS)** — except via solids transport
- **Other emitters** — no emitter-to-emitter material transfer
- **Any gaseous CO₂ handling equipment connected to PS**

4.2.4 Rationale

This boundary enforces HOPT's foundational principle:

Emitters do NOT participate in the gaseous CO₂ network.

4.3 Boundary 2 — Solids Logistics System (SLS) Boundary

The **Solids Logistics System boundary** covers the physical flow of solid materials between emitters and hubs.

4.3.1 What Lies Inside This Boundary

- Road/rail/barge transport units
- Containerized solids handling

- Sealed bins, hoppers, or tankers
- Logistics scheduling systems
- Chain-of-custody digital tracking
- Loading/unloading equipment in transport domain

4.3.2 Allowed Interfaces

SLS interfaces with:

- **Emitters (ES)** — outbound/inbound solids
- **Hubs (HS)** — outbound/inbound solids
- **HOPT Registry** — digital lifecycle documentation

4.3.3 Prohibited Interfaces

SLS must NOT:

- Handle gaseous CO₂,
- Engage in regeneration or capture,
- Connect to pipeline systems,
- Alter or reformulate solids chemical composition,
- Route materials between emitters without hub processing.

4.3.4 Rationale

Maintains strict function separation: logistics ≠ processing

4.4 Boundary 3 — Hub System (HS) Boundary

The **Hub System boundary** encloses all activities required to:

- Regenerate CO₂ gas from solids,
- Produce pipeline-grade CO₂,
- Cycle sorbent back to emitters,
- Interface with pipeline systems at injection/withdrawal points.

4.4.1 What Lies Inside This Boundary

- Solids receiving station
- CO₂ regeneration reactors (e.g., calciners, flash units)
- Gas cleaning and conditioning systems

- CO₂ compression trains
- Hub storage (short-term solids/material)
- Hub supervisory controls
- Hub pressure/flow coordination systems
- Safety interlocks for regeneration and gas handling
- Interface manifold to pipeline system

4.4.2 Allowed Interfaces

HS interfaces with:

1. **SLS** — solids in/out
2. **Pipeline System (PS)** — gas injection/withdrawal
3. **Storage/Utilization System (SUS)** — via PS routing
4. **Hub Developer / EPC / Regulator** — local compliance and construction
5. **HOPT Registry** — hub certification, solids/CO₂ accounting

4.4.3 Prohibited Interfaces

HS may **not**:

- Dispatch gaseous CO₂ directly to emitters,
- Allow emitters to bypass hub operations,
- Accept gaseous CO₂ from emitters,
- Generate private “hub-to-every-emitter” mini-networks,
- Interface directly with Storage except through pipelines.

4.4.4 Rationale

Centralizing regeneration/gas-handling at hubs is **HOPT’s fundamental architecture**.

4.5 Boundary 4 — Pipeline System (PS) Boundary

The **Pipeline System boundary** defines all pipeline infrastructure and hub-to-hub CO₂ flow.

4.5.1 What Lies Inside This Boundary

- Transmission pipelines
- Branch pipelines (hub-to-hub only)
- Injection/withdrawal risers at hubs

- Pipeline compressors and booster stations
- SCADA/telemetry
- Pressure control stations
- Isolation, interception, and emergency systems

4.5.2 Allowed Interfaces

PS interfaces exclusively with:

- **Hubs (HS)** — at designated pipeline manifold points
- **Storage/Utilization (SUS)** — downstream terminals
- **Pipeline Operators** — control and oversight
- **Permitting authorities** — regulatory compliance

4.5.3 Prohibited Interfaces

PS must NOT:

- Connect to emitters,
- Accept gaseous CO₂ from any non-hub source,
- Distribute CO₂ to emitters or logistic facilities,
- Route through logistics depots or emitter yards,
- Interface with solids systems.

4.5.4 Rationale

This ensures the pipeline network remains **clean, consistent, safe, and scalable**.

4.6 Boundary 5 — Storage & Utilization System (SUS) Boundary

The **SUS boundary** includes all final CO₂ disposition systems.

4.6.1 What Lies Inside This Boundary

- Injection wells
- Surface facilities for dehydration, heating, metering
- Pressure management systems
- MRV instrumentation
- Utilization plants/processes
- Data systems for verification and reporting

4.6.2 Allowed Interfaces

SUS interfaces with:

- **Pipeline System (PS)** — receiving pipeline-grade CO₂
- **HOPT Registry** — MRV-based carbon accounting
- **Regulators** — reporting and verification

4.6.3 Prohibited Interfaces

SUS must NOT:

- Receive CO₂ directly from emitters,
- Accept CO₂ in solids form,
- Handle regeneration or solid-gas conversion,
- Integrate directly with hub capture equipment.

4.6.4 Rationale

Maintains clean separation of:

capture → logistics → regeneration → transport → storage.

4.7 Cross-Boundary Rules (Normative)

To preserve topology purity:

Rule A — No Emitter–Pipeline Interface

This rule is absolute.

If violated, the system is not HOPT.

Rule B — No Regeneration Outside Hubs

Gas-phase CO₂ release must be centralized.

Rule C — Logistics Must Not Cross Into Pipeline Functions

SLS cannot evolve into pipeline-like operations.

Rule D — Pipeline System Must Not Serve Emitters

Deployments must not drift toward traditional pipeline CCUS.

Rule E — Storage Must Use Pipeline-grade CO₂ Delivered via PS

Ensures consistent MRV, pressure management, and safety standards.

Rule F — All Cross-boundary flows must use approved HOPT-AS interfaces

No proprietary shortcuts.

Rule G — All participating systems must be registered under Novonanmek-administered HOPT certification and registry systems

Ensures traceability and governance

4.7 Relationship between Architectural Boundaries and Dynamic Compliance

The architectural boundaries established by HOPT-AS define the permitted sources of CO₂, stakeholder relationships, infrastructure interfaces, and functional interactions that collectively preserve the system-level risk mitigation characteristics embodied within the applicable HOPT-AS Architecture Class.

Unlike conventional CCUS architectures, the Hub-Only Pipeline Topology intentionally decouples emitters from the common transportation network by requiring CO₂ to enter the network through Regeneration Hubs rather than through direct pipeline connections. While this architectural approach provides significant benefits in scalability, flexibility, interoperability, and system-level risk mitigation, it also necessitates continuous verification that CO₂ accepted into the HOPT network originates only from sources, processes, and stakeholder relationships that are consistent with the architectural boundaries established by this Standard.

Accordingly, Dynamic Compliance shall maintain the integrity of these architectural boundaries throughout the lifecycle of a HOPT implementation. Any deviation from the established architectural boundaries shall be considered an architecturally significant change and shall be evaluated in accordance with the Dynamic Compliance requirements of this Standard.

SECTION 5 — TOPOLOGY CLASSES & ALLOWED CONFIGURATIONS

(Normative)

HOPT-AS defines a limited, governed set of **Topology Classes** that describe permissible system-level configurations of hubs, emitters, logistics, and pipelines.

A system claiming HOPT compliance **must fit entirely** within one of the allowed topology classes defined in this section.

A topology configuration outside these classes is NOT HOPT-compliant.

Topology classes define:

- How hubs connect to each other,
- How emitters cluster around hubs,
- How solids logistics routes are structured,
- How pipelines form the hub-to-hub network,
- How storage interfaces are arranged.

The classes are designed for scalability, interoperability, and governance consistency across regions.

5.1 Overview of HOPT Topology Classes

All HOPT system deployments belong to one of the following classes:

Topology Class A — Single Hub / Many Emitters (A-1, A-2)

A single HOPT hub serving many emitters; no pipeline network

Topology Class B — Multi-Hub Linear Network (B-1, B-2)

Two or more hubs connected by a linear (non-branching) pipeline corridor.

Topology Class C — Multi-Hub Branched Network (C-1, C-2)

A hub-to-hub pipeline network with selective branching, but no emitter connection at any point

Topology Class D — Regional Hub Cluster Network (D-1, D-2, D-3)

A fully interconnected regional hub network with flexible routing and dynamic CO₂ balancing

Topology Class E — Hub + Multi-Storage Architecture (E-1, E-2)

Hubs connected to multiple storage sites or sinks.

Each class has **sub-classes** that define scaling or logistics variants.

5.2 Topology Class A — Single Hub / Many Emitters

This is the simplest HOPT deployment and the natural starting configuration for early adopters.

A-1: Single Hub, Direct Solids Logistics Feed

- One hub (HS)
- Multiple emitters (ES1...ESn)
- Solids Logistics System (SLS) routes materials directly
- No pipelines
- Storage is co-located with the hub or pipeline-free

Allowed:

- Any number of emitters connected via SLS
- Local or onsite storage
- Multiple logistics modes (road/rail)

Forbidden:

- Adding pipelines from the hub to emitters
- Regeneration at emitters
- Emitter-to-emitter routing

A-2: Single Hub with Feeder Logistics Stations

- Emitters send solids to intermediate logistics consolidation nodes
- Nodes forward solids to hub
- Useful in dense industrial zones

Allowed:

- Shared logistics nodes
- Consolidation/aggregation
- Regional routing optimization

Forbidden:

- CO₂ regeneration at nodes
- Any gaseous handling outside the hub

5.3 Topology Class B — Multi-Hub Linear Pipeline Network

This class introduces pipelines exclusively between hubs.

B-1: Two-Hub Linear System

- Hub H1 connects to Hub H2 via PS (pipeline system)
- Emitters cluster around each hub

Allowed:

- Balanced or unbalanced hub sizes
- Bi-directional or unidirectional pipeline operation

Forbidden:

- Side branches from H1 → emitters
- CO₂ injection at emitters

B-2: Three-Hub Corridor

- H1 → H2 → H3, forming a linear chain
- Emitters cluster around any hub

Allowed:

- Multiple emitters per hub
- Logistics differentiation by region

Forbidden:

- Emitter bypass to any hub-to-hub route
- Adding pipeline segments to emitters

5.4 Topology Class C — Multi-Hub Branched Networks

Topology C introduces branching while retaining strict hub-only gas routing.

C-1: Branching Three-Hub System

- H1 connects to H2 and H3
- H2 and H3 do not interconnect

Allowed:

- Branching pipeline structure

- Independent emitter clusters at each hub

Forbidden:

- Emitter in-line connection
- Hub acting as logistics transfer point (solid→solid only via SLS)

C-2: Hub Spoke + Sub-Branch

- $H1 \rightarrow H2$
- $H1 \rightarrow H3$
- Sub-branch $H3 \rightarrow H4$

Allowed:

- Multi-regional CO₂ routing
- Load balancing between hubs

Forbidden:

- Hub-to-emitter pipelines
- Regeneration nodes outside hub boundaries

5.5 Topology Class D — Regional Cluster Networks (Fully Interconnected)

This class represents large-scale, national CCUS infrastructure.

D-1: Fully Connected Cluster

- $H1 \leftrightarrow H2 \leftrightarrow H3 \leftrightarrow H4$
- Every hub can route CO₂ to every other hub (directly or indirectly)

Allowed:

- Dynamic CO₂ balancing
- Multiple logistics regimes
- Hub redundancy

Forbidden:

- Off-network hubs
- Local emitter pipelines

D-2: Cluster with Ring Pipeline

- Circular topology

- $H1 \leftrightarrow H2 \leftrightarrow H3 \leftrightarrow H4 \leftrightarrow H1$
- Provides high reliability and load balancing

D-3: Cluster with Hierarchical Hub Structure

- Primary hubs (PH)
- Secondary hubs (SH)
- PHs interconnect; SHs branch from PHs

Allowed:

- Large-scale CO₂ routing
- Priority load-balancing at PH-level

Forbidden:

- SH-to-emitter gas routing

5.6 Topology Class E — Hub + Multi-Storage Architecture

Here the hub connects to multiple sinks.

E-1: One Hub to Multiple Storage Sites

- Single hub → multiple storage options
- Pipeline branching occurs **downstream**, not upstream

Allowed:

- Sink-specific pressure/temperature conditioning
- Seasonal/strategic injection allocation

Forbidden:

- Storage → emitter routing
- Solids-to-storage transport (must be gas-phase)

E-2: Multi-Hub, Multi-Storage Mesh

- Hubs connect to multiple storages
- Storages may be shared across hubs

Allowed:

- Multi-sink flexibility
- National CO₂ management architectures

Forbidden:

- Storage acting as a hub
- Emitter-to-storage direct connections

5.7 Non-Compliant Topologies (Explicitly Forbidden)

To prevent drift into conventional CCUS or hybridized ungoverned systems, the following topologies are strictly *forbidden*:

F-1: Emitter Pipeline Tap-In

Any emitter connected to a CO₂ pipeline is a violation.

F-2: Distributed Regeneration Topologies

Regeneration outside a certified hub is not permitted.

F-3: Hub-less Pipeline

Pipeline-only networks without hubs are invalid.

F-4: Hub-to-Emitter Micro-Pipelines

No matter the capacity or pressure.

F-5: Emitter-to-Emitter Solids Exchange without Hub Processing

No direct emitter interdependence.

F-6: Storage Connected to Emitters

Storage must receive pipeline-grade CO₂ only from the pipeline system.

F-7: Mixed-Mode Networks Combining HOPT and Conventional CCUS without Clear Separation - Hybrid networks require Novonanmek-approved boundaries.**5.8 Governing Rules for Selecting a Topology Class**

All HOPT deployments must follow:

Rule 1 - Every configuration must fit exactly into one class.

A deployment cannot be “between classes.”

Rule 2 - A system may transition topology classes only with formal written approval issued by Novonanmek

Scaling must be governed.

Rule 3 - Only topology families defined in this section may be used.

No private variants.

Rule 4 - Class selection dictates hub class, logistics type, and allowable expansion.**Rule 5 - Every emitter must belong to one and only one hub’s solids network.**

SECTION 6 — PARTICIPATION AND DYNAMIC COMPLIANCE REQUIREMENTS

(Normative)

Participation in the Hub-Only Pipeline Topology (HOPT) is governed by defined stakeholder eligibility requirements, architectural responsibilities, and Dynamic Compliance obligations established by this Standard.

HOPT is an open architecture whose participating emitters, regeneration hubs, logistics pathways, pipeline infrastructure, storage facilities, and supporting systems may evolve throughout the operational lifecycle of the infrastructure. Such evolution is both expected and encouraged in order to support scalable deployment. However, all infrastructure evolution shall preserve the defining characteristics of the applicable HOPT Architecture Class.

Accordingly, participation in a HOPT implementation extends beyond initial eligibility or technical conformance. Every participating entity assumes an ongoing responsibility to ensure that its activities, decisions, and modifications remain consistent with the governing architectural principles of HOPT-AS and do not result in Architectural Drift.

Dynamic Compliance is therefore a mandatory obligation applicable to all participating entities. Each participant shall conduct its activities in a manner that preserves the integrity, interoperability, scalability, and risk-mitigating characteristics of the applicable Architecture Class throughout the operational lifecycle of the infrastructure system.

The requirements contained in this section are normative and shall be satisfied by all participating entities claiming conformity with HOPT-AS.

6.1 Categories of Participating Entities

A participating entity shall perform one or more defined architectural roles within a HOPT implementation.

The stakeholder categories recognized by HOPT-AS are:

1. Emitter (E)
2. Hub Developer / Hub Operator (HD/HO)
3. Pipeline Operator (PO)
4. Solids Logistics Provider (SLP)
5. Storage / Utilization Operator (SUO)
6. Capture Technology Vendor (CTV)
7. EPC Contractor / System Integrator (optional)
8. Digital Monitoring, Data Management, or MRV Service Provider (optional)

An organization may perform multiple stakeholder roles, provided that the responsibilities and obligations associated with each role are satisfied independently.

Participation within one stakeholder category does not exempt a participant from the Dynamic Compliance obligations applicable to all HOPT participants.

6.2 General Participation Obligations

Every participating entity shall:

- a) comply with the applicable normative requirements of HOPT-AS;
- b) operate only within the architectural responsibilities assigned to its stakeholder category;
- c) preserve the defining characteristics of the applicable HOPT Architecture Class;
- d) cooperate with other participating entities where necessary to preserve overall architectural integrity;
- e) ensure that proposed modifications under its control do not result in Architectural Drift;
- f) provide information reasonably necessary to demonstrate continued Dynamic Compliance where such demonstration is required; and
- g) refrain from representing infrastructure as conforming to HOPT-AS where Dynamic Compliance is no longer maintained.

6.3 Dynamic Compliance Obligations

Dynamic Compliance is a continuous architectural obligation applying throughout the operational lifecycle of every HOPT implementation.

Accordingly, every participating entity shall ensure that changes under its control preserve compliance with the applicable Architecture Class.

Architecturally significant changes include, but are not limited to:

- addition or removal of participating emitters;
- reassignment of emitters between regeneration hubs;
- establishment or modification of solids logistics pathways;
- development or expansion of regeneration hubs;
- construction or modification of hub-to-hub pipeline infrastructure;
- changes affecting system boundaries;
- transition between Architecture Classes; and
- any other modification capable of affecting the defining characteristics of the applicable Architecture Class.

Where a proposed change may affect the architectural integrity of the HOPT implementation, the participant responsible for that change shall ensure that the change is evaluated in accordance with the Dynamic Compliance requirements of this Standard before implementation.

No participant shall knowingly undertake or authorize actions that would compromise the defining characteristics of the applicable Architecture Class or result in Architectural Drift.

6.4 Collective Architectural Responsibility

The preservation of a HOPT implementation is a shared responsibility.

While individual participants remain responsible for activities under their own control, the architectural integrity of the HOPT implementation depends upon coordinated compliance by all participating entities.

Accordingly, no participant shall implement modifications that preserve local objectives while undermining the long-term architectural integrity, interoperability, scalability, or governing principles of the overall HOPT implementation.

6.5 Continuing Participation

Participation within a HOPT implementation shall be regarded as continuous rather than event-based.

Initial conformity with HOPT-AS does not, by itself, establish continuing conformity.

A participating entity shall remain in conformity with this Standard only while its activities continue to preserve Dynamic Compliance with the applicable Architecture Class throughout the operational lifecycle of the infrastructure system.

Where Dynamic Compliance is no longer maintained, the affected implementation shall not be represented as conforming to HOPT-AS until compliance with the applicable Architecture Class has been restored.

SECTION 7 — DEPLOYMENT MODELS & SCALING BEHAVIOR

(Normative)

HOPT-AS enables a structured, scalable pathway for deploying CCUS infrastructure using the Hub-Only Pipeline Topology.

The topology classes described in Section 5 are not intended to be static; systems naturally **evolve**, **expand**, and **scale** through defined growth stages. This section provides a governed framework for such evolution.

Scaling behaviour under HOPT-AS is **normative**; meaning deviations from the prescribed evolution pathways require formal written approval or interpretation issued by Novonanmek.

7.1 Purpose of Deployment Models

Deployment models allow:

- Predictable regional growth,
- Compatible expansions,
- Controlled infrastructure investment,
- Gradual increase in complexity,
- Interoperability across phases,
- Consistency across national decarbonization plans.

Without structured models, CCUS deployments risk becoming fragmented or incompatible.

7.2 Deployment Archetypes (informative – Non-normative)

HOPT-AS may be deployed across multiple physical and organizational scales while preserving the same foundational topology principles.

Illustrative deployment archetypes include:

Deployment Type	Description
Type A — Intra-Facility Distributed Emitter HOPT	Multiple emitter nodes located within a single industrial facility or industrial campus interface with one or more centralized regeneration hubs through internal solids logistics systems.
Type B — Industrial Cluster HOPT	Multiple industrial facilities within a geographic cluster interface with shared centralized regeneration hubs through regional solids logistics systems.
Type C — Regional Multi-Hub HOPT	Multiple hubs serving multiple industrial clusters are interconnected through a regional or national hub-to-hub CO ₂ pipeline backbone.

7.3 Deployment Model Stages

HOPT deployments typically evolve through **four major stages**:

1. **Stage 1: Single-Hub Early Deployment (Class A)**
2. **Stage 2: Multi-Hub Linear Scaling (Class B)**
3. **Stage 3: Regional Network Formation (Class C / early D)**
4. **Stage 4: National-Scale CCUS Mesh (Class D and E)**

These stages are not mandatory but represent the standard's recommended growth trajectory.

7.4 Stage 1 — Single-Hub Early Deployment (Class A)

7.4.1 Description

Deployment begins with a single, centrally located hub serving a local cluster of emitters. This model minimizes capital expenditure and allows early commercial operation without pipeline infrastructure.

7.4.2 Characteristics

- One Hub (H_1)
- Many Emitters ($E_1 \dots E_n$)
- Solids logistics only
- No gaseous CO_2 pipelines
- Possible onsite or near-site storage and/or utilization

7.4.3 Advantages

- Fastest path to operational CCUS
- Least regulatory burden
- Simplest governance
- Lowest CapEx
- Ideal for “demonstrate and scale”

7.4.4 Compliance Constraints

- Emitters must not install regeneration or pipeline connections
- Solids logistics must follow Section 4 boundary rules
- Hub must be Dynamically Compliant

7.5 Stage 2 — Multi-Hub Linear Scaling (Class B)

After a single hub is successful, demand grows and multiple hubs emerge.

7.5.1 Description

Two or more hubs are deployed across a region and linked by **linear pipelines** (H_1-H_2 or $H_1-H_2-H_3$).

7.5.2 Characteristics

- Hub-to-hub pipeline corridor
- Distributed emitters around each hub
- Early form of shared infrastructure
- Regional solids logistics network

7.5.3 Advantages

- Enables regional flexibility
- Allows CO₂ balancing between hubs
- Introduces economies of scale
- Storage/utilization may be centralized or distributed

7.5.4 Governance Notes

- Pipeline Operators must be certified
- Emitters remain solids-only participants
- Pipeline routing must not connect to emitters

7.5.5 Evolution Path

This stage typically evolves toward:

- Branching networks (Class C), or
- Fully connected clusters (D).

7.6 Stage 3 — Regional Network Formation (Class C / early D models)

7.6.1 Description

Once multiple linear pipelines exist, branching patterns emerge, forming early-stage **regional CO₂ networks**.

7.6.2 Characteristics

- 3–5 hubs across a region
- At least one branch or sub-branch
- Interconnected solids logistics and pipeline flows
- HOPT-compliant clusters

7.6.3 Advantages

- Regional optimization of CO₂ routing
- Better redundancy and reliability
- Multiple peripheral emitters can join
- Greater storage flexibility

7.6.4 Governance Requirements

- Hubs must align with assigned **Hub Class**
- Topology must strictly fit Class C or early D
- Any deviation requires formal written approval or interpretation issued by Novonanmek
- MRV systems must be centrally coordinated across region
- All hubs must share compatibility formats for CO₂ quality and solids class

7.6.5 Transition Triggers

A system typically transitions to Stage 3 when:

- more than 2 hubs are needed,
- pipeline flows exceed hub-to-hub balancing limits,
- emitters grow beyond logistics capacity of a single hub,
- a region evaluates multiple storage sites.

7.7 Stage 4 — National-Scale CCUS Mesh (Class D/E)

7.7.1 Description

At higher maturity levels, regions interconnect into a national mesh of hubs and pipeline corridors, forming a full HOPT network.

7.7.2 Characteristics

- 5+ hubs linked into a mesh
- Redundant routing paths
- High CO₂ mobility across network
- Multi-line pipeline corridors
- Multiple storage sites (Class E variants)

7.7.3 Advantages

- Industry-scale, long-term CCUS backbone
- High reliability
- Flexible injection strategies
- Optimized utilization of national storage basins

- Ability to absorb large emitters and seasonal variations
- Low-cost CO₂ balancing among hubs

7.7.4 Governance Requirements

- National HOPT Registry integration
- Unified MRV and chain-of-custody protocols
- All topology nodes must remain HOPT-compliant
- Pipeline Operators require national-scale certification
- Hub Classes must be harmonized across regions
- Storage operations require HSC certification

7.7.5 Compatibility Requirements

- Every new hub must conform to a recognized Hub Class (from Section 5)
- Pipeline corridors must not include emitter taps
- Logistics patterns must remain solids-based for emitters

7.8 Scaling Behaviour Principles

Scaling under HOPT-AS follows these architectural norms:

7.8.1 Principle of Topology Integrity

A system cannot change topology classes without formal written approval or interpretation issued by Novonanmek

7.8.2 Principle of Indivisibility

Emitters cannot be split across hubs; each emitter belongs to **one** solids network unless re-certified.

7.8.3 Principle of Progressive Maturity

Class A → Class B → Class C/D is the recommended path.
Direct jumps (e.g., A → D) require special governance reviews.

7.8.4 Principle of Centralized Gaseous Handling

As scaling increases, the requirement to maintain gas-handling exclusively at hubs becomes even more critical.

7.8.5 Principle of Modular Expansion

Each new hub must integrate cleanly into the topology family chosen for the region.

7.9 Regional and National Planning Alignment

HOPT-AS supports:

- Municipal decarbonization plans,
- State-level industrial cluster planning,

- National CO₂ pipeline corridor development,
- Long-term infrastructure amortization.

Novonanmek may work with governments to define:

- Recommended hub spacing,
- Expected corridor routes,
- Planning buffers for future expansion.

7.10 Distributed Storage Scaling (Class E)

At large scale, multiple storage basins are used.

7.10.1 Routing Rules

- Hubs may route to multiple storages,
- Storage may be shared between hubs,
- Pipeline design must prevent emitter-side pathways.

7.10.2 MRV Integrity

Multiple storage sites require robust chain-of-custody.

7.11 Summary of Deployment Patterns

HOPT allows regions to begin **small**, prove commercial value, and scale gradually into **national CO₂ management ecosystems**—all without losing architectural integrity.

- **Stage 1:** Simple, fast deployment
- **Stage 2:** Regional linear systems
- **Stage 3:** Multi-hub networks
- **Stage 4:** National meshes with multi-storage routing

Throughout all stages, the topology rules remain fixed:

Emitters → Solids Logistics → Hub → Pipeline → Storage (No exceptions)

SECTION 8 — MRV, CARBON ACCOUNTING & CHAIN-OF-CUSTODY FRAMEWORK

(Normative)

Measurement, Reporting, Verification (MRV) and Chain-of-Custody (CoC) form the **digital compliance and carbon-tracking architecture** of HOPT-AS.

Because HOPT involves multi-stakeholder interaction, solids transport, centralized regeneration, and multi-hub pipeline networks, a clear and enforceable MRV and CoC framework is essential to ensuring:

- Carbon-accounting integrity,
- Regulatory acceptance,
- Crediting eligibility,
- Safety oversight,
- Prevention of double counting, and
- Multi-stakeholder interoperability.

This section is **normative**.

All HOPT-certified entities must comply with MRV & CoC requirements.

8.1 Purpose of MRV in HOPT

MRV in HOPT ensures:

1. **CO₂ mass-balance integrity** across solids, hubs, pipelines, and storage.
2. **Traceability** from emitter → hub → storage.
3. **Compatibility** with national/international carbon markets.
4. **Transparency** for multi-party CCUS-as-a-Service.
5. **Regulatory confidence** in captured, transported, and stored CO₂ volumes.
6. **Verification** of emissions reductions and storage permanence.

8.2 MRV Architecture Overview

HOPT MRV architecture includes:

- **Emitter MRV** (solid-phase accounting)
- **Logistics MRV** (transport chain-of-custody)
- **Hub MRV** (regeneration + conditioning)
- **Pipeline MRV** (flow, pressure, metering)
- **Storage MRV** (injection + permanence)
- **HOPT Registry** (digital backbone)

Each subsystem reports into a centralized digital Registry maintained by Novonanmek as part of the HOPT certification framework

8.3 Chain-of-Custody (CoC) Principles

The following CoC principles apply system-wide:

8.3.1 Principle of Continuity

Every unit of CO₂ must have a continuous traceable record from capture to storage.

8.3.2 Principle of Non-Substitution

CO₂ captured at one emitter cannot be swapped or substituted with CO₂ from another emitter unless explicitly permitted and logged in the Registry.

8.3.3 Principle of Non-Commingling (Solids Stage)

Before regeneration, emitter-specific solids must remain traceable and not mixed in a way that breaks traceability.

(After regeneration, gaseous CO₂ may be commingled under pipeline accounting rules.)

8.3.4 Principle of Identity Preservation through Regeneration

The moment solids are delivered to a hub, the hub assumes custody and assigns batch identifiers linking incoming solids to outgoing CO₂.

8.3.5 Principle of Digital Verification

All CoC events must be digitally logged in the HOPT Registry.

8.4 MRV Responsibilities by Stakeholder Category

8.4.1 Emitters — Solid Phase MRV

Emitters must measure and report:

- Mass of solids loaded with CO₂,
- CO₂ loading fraction per unit of solids,
- Batch ID, timestamp, and quality logs,
- Solids mass returned from hubs,
- Emissions reductions achieved.

Instrumentation must include:

- Mass-flow or weighbridge systems,
- Batch tracking QR/Rfid systems,
- CO₂ loading estimation instruments,
- On-site calibration capability.

Emitters must NOT record gaseous CO₂ injection volumes (they are not pipeline participants).

8.4.2 Logistics Providers — Transport MRV

Logistics providers must track:

- Solids pickup and drop-off weights,
- Batch ids and custody transfers,
- Door-sealed integrity checks,
- Deviations, spills, or anomalies,
- Transit-time and pathway logs.

SLPs must use HOPT-approved:

- Digital CoC tags (QR, RFID, NFC),
- GPS/telematics systems,
- Digital manifest submission.

8.4.3 Hubs — Regeneration and Gas-Phase MRV

Hubs must measure:

1. **Incoming solids metrics**
 - Total solids mass
 - CO₂ content estimation
 - Batch alignment logs
2. **Regeneration metrics**
 - CO₂ released per batch
 - Heat input and energy balance
 - Sorbent degradation losses
 - Solids regeneration output
3. **Pipeline-grade output metrics**
 - Co₂ purity
 - Pressure and temperature
 - Flow rate
 - Metered injection volume
4. **Return solids metrics**
 - Regenerated solids quantity, quality, and traceability

Hubs must maintain continuous metering with redundancy.

8.4.4 Pipeline Operators — Transport MRV

Pipeline MRV includes:

- Injection volume metering per hub,
- Withdrawal metering (if applicable),
- Pressure and flow telemetry,
- SCADA logs for pipeline operations,
- Compression station energy use (optional reporting),
- Leak detection and anomaly reporting.

Pipeline operators must submit these data to the registry maintained by Novonanmek as part of the HOPT certification framework in near real-time.

8.4.5 Storage Operators — Storage MRV

Storage operators must track:

- Injection volumes per hub,
- Injection well pressures,
- Formation monitoring data,
- Permanence assurance data,
- Leakage tests,
- Operational shutdown logs,
- Compliance with national CCS regulations.

Storage MRV must be matched to pipeline MRV such that CO₂ delivered = CO₂ injected (minus pipeline linepack adjustments).

8.5 Digital HOPT Registry Requirements

The HOPT Registry is the **authoritative MRV and CoC platform**, maintained by Novonanmek as part of the HOPT certification framework.

It must include:

- All participant registrations and certifications,
- CoC logs from emitters, logistics, hubs, pipelines, storage,
- Volume-based carbon accounting,
- Batch tracking for solids and CO₂,
- Discrepancy detection,
- Reconciliation algorithms,
- Audit logs.

8.5.1 Required Data Model Elements

For each CO₂ batch or flow:

- Unique identifier (UUID)
- Origin emitter ID
- Mass of solids
- CO₂ loading
- Transport logs
- Hub processing logs
- Pipeline metering logs
- Storage injection logs
- Time-stamped chain of custody

8.5.2 Integration Requirements

Registry must integrate with:

- IOT sensors,
- SCADA,
- Telematics,
- ERP systems (optional),
- Emissions reporting portals.

8.6 Carbon Accounting Rules

HOPT-AS uses a combination of:

- **Mass-balance accounting,**
- **Batch-level tracking,** and
- **Pipeline-network flow accounting.**

Carbon accounting must:

- Prevent double counting,
- Maintain emitter-specific reductions,
- Track carbon from origin to sink.

8.6.1 Emitter Credit Assignment

An emitter receives credit for:

- **CO₂ captured, transported, and stored**
- Validated through the registry.

8.6.2 Hub-Level Accounting

Hubs must:

- Link incoming solid batches to outgoing CO₂ volumes,
- Log losses or discrepancies,
- Maintain solids-loop audit trails.

8.6.3 Pipeline-Level Accounting

Pipeline operators must:

- Maintain accurate injection and withdrawal metering,
- Track linepack adjustments,
- Prevent emissions or leaks.

8.6.4 Storage-Level Accounting

Storage operators must:

- Match injected CO₂ with metered deliveries,
- Ensure MRV protocols confirm permanence.

8.7 Verification Requirements

Verification is performed by:

- Accredited 3rd-party verifiers, or
- Novonanmek-approved verification bodies.

Verification includes:

- Independent audit of MRV data,
- Mass balance reconciliation,
- On-site inspections,
- Validation of registry entries.

Novonanmek must approve verification methodologies.

8.8 Exceptions, Corrections & Reconciliation

HOPT-AS allows controlled correction processes:

8.8.1 Acceptable Variances

Minor variances ($\leq 1\text{--}2\%$) permitted for:

- Measurement error,
- Moisture correction,
- Linepack drift.

8.8.2 Reportable Variances

$\geq 3\text{--}5\%$ must trigger:

- Variance report,
- Corrective action plan,
- Potential investigation.

8.8.3 Non-Compliant Variances ($> 5\%$)

Require:

- Immediate reporting,
- Hub or pipeline investigation,

- Possible certification review.

8.9 Data Retention & Privacy Requirements

All MRV data must be retained for a minimum of:

- **10 years** for stored CO₂
- **5 years** for logistics data
- **full contract lifetime** for emitters and hubs

Novonanmek must ensure:

- Secure storage,
- Controlled access,
- Privacy of commercially sensitive information.

8.10 Compatibility with National/International Carbon Markets

HOPT MRV must support:

- Article 6 mechanisms (Paris Agreement),
- National ETS programs,
- Corporate Scope 1/2/3 reporting,
- Carbon credit methodologies (e.g., 45Q-like systems).

Novonanmek may issue:

- MRV addendums
- Region-specific compliance frameworks
- Storage verification harmonization guidelines

8.11 Relevance to Dynamic Compliance

The effectiveness of the MRV and Chain of Custody framework established by this Standard is dependent upon the continued preservation of the architectural boundaries established in Clause 4.7 through Dynamic Compliance. MRV and Chain of Custody shall therefore operate in conjunction with the Dynamic Compliance requirements to ensure that CO₂ accepted into the HOPT network remains consistent with the architectural boundaries, stakeholder relationships, and functional assumptions established by the applicable HOPT-AS Architecture Class

8.12 Summary

This section formalizes:

- Full CO₂ lifecycle accounting,

- Batch-level traceability,
- Consistent and verifiable MRV integration,
- Compatibility with pipeline operations,
- Regulatory-aligned storage validation,
- Protection against double counting or reporting drift.

It forms the *digital backbone* of the HOPT ecosystem.

SECTION 9 — DYNAMIC COMPLIANCE AND ARCHITECTURAL CONFORMANCE

(Normative)

9.1 Purpose

Dynamic Compliance is an integral and indispensable component of HOPT-AS and shall not be regarded as an additional administrative, auditing, certification, or governance requirement.

HOPT-AS establishes an architectural framework specifically designed to achieve defined system-level risk mitigation characteristics. These risk mitigation characteristics arise from the preservation of the architectural principles, Architecture Classes, relationships, interfaces, and other architecturally significant requirements established by this Standard.

HOPT implementations are inherently evolutionary. Throughout their lifecycle, infrastructure may be expanded, modified, integrated with additional emitters, regeneration hubs, pipelines, storage facilities, utilization facilities, logistics systems, and other architecturally significant infrastructure. Similarly, planning decisions, engineering designs, procurement activities, supplier proposals, technology selections, construction modifications, operational changes, and infrastructure expansion may progressively influence the architectural characteristics of the implementation.

Without continuous architectural oversight, such changes may introduce Architectural Drift, resulting in the progressive degradation of the system-level risk mitigation characteristics embodied within the applicable HOPT-AS Architecture Class.

Accordingly, Dynamic Compliance has been incorporated into HOPT-AS as the mechanism by which architecturally significant decisions and infrastructure changes are continuously evaluated throughout planning, design, procurement, construction, commissioning, operation, expansion, modification, and long-term stewardship to ensure that the applicable Architecture Class, and the associated system-level risk mitigation characteristics established by this Standard, are continuously preserved.

Dynamic Compliance is therefore fundamental to the effective implementation of HOPT-AS and is necessary to ensure that the Standard continues to deliver its intended system-level risk mitigation outcomes throughout the entire lifecycle of a HOPT implementation.

9.2 Architectural Conformance

Architectural Conformance is the condition in which an infrastructure implementation continues to preserve the defining characteristics of the applicable HOPT Architecture Class.

Architectural Conformance differs from engineering conformance.

Engineering conformance demonstrates that individual assets have been designed, constructed, commissioned, and operated in accordance with applicable engineering, regulatory, and safety requirements.

Architectural Conformance demonstrates that the infrastructure system, as a whole, continues to preserve the governing principles, topology, system boundaries, interoperability characteristics, and structural relationships defined by the applicable Architecture Class.

HOPT-AS governs Architectural Conformance.

Engineering conformance remains the responsibility of project owners, designers, contractors, operators, and applicable regulatory authorities.

9.3 Initial and Continuing Conformance

Conformance with HOPT-AS consists of two complementary conditions.

9.3.1 Initial Conformance

Initial Conformance is achieved when an infrastructure implementation satisfies the normative requirements of HOPT-AS at the time of deployment and conforms to an identified Architecture Class.

Initial Conformance establishes that the implemented infrastructure possesses the defining characteristics of the applicable Architecture Class at the time it enters service.

9.3.2 Continuing Conformance

Because HOPT is an open architecture, Initial Conformance alone does not establish continuing conformity.

Continuing Conformance exists only while Dynamic Compliance is maintained throughout the operational lifecycle of the infrastructure system.

An implementation that was initially conforming may subsequently lose Architectural Conformance if infrastructure evolution results in Architectural Drift.

9.4 Dynamic Compliance

Dynamic Compliance is the continuous preservation of the defining characteristics of the applicable HOPT Architecture Class throughout the planning, deployment, operation, expansion, modification, and long-term evolution of the infrastructure system.

Dynamic Compliance shall be maintained by every implementation claiming conformity with HOPT-AS.

Dynamic Compliance applies to all architecturally significant changes, irrespective of whether those changes are technical, operational, commercial, organizational, or ownership-related.

Dynamic Compliance shall ensure that infrastructure evolution preserves:

- the applicable Architecture Class;
- the governing principles of the Hub-Only Pipeline Topology;
- mandatory system boundaries;
- topology constraints;
- interoperability requirements;
- stakeholder responsibilities;
- scalability characteristics; and
- the system-level risk mitigation properties upon which the applicable Architecture Class is founded.

9.5 Architecturally Significant Change

An **Architecturally Significant Change** is any modification capable of affecting the defining characteristics of the applicable HOPT Architecture Class.

Architecturally Significant Changes include, but are not limited to:

- addition or withdrawal of participating emitters;
- reassignment of emitters between regeneration hubs;
- establishment, modification, or removal of solids logistics pathways;
- development, expansion, consolidation, or retirement of regeneration hubs;
- construction, expansion, or modification of hub-only pipeline infrastructure;
- changes affecting stakeholder responsibilities;
- changes affecting interoperability;
- changes affecting mandatory system boundaries;
- transition between Architecture Classes; and
- any other modification capable of altering the architectural identity of the implementation.

Every Architecturally Significant Change shall preserve Dynamic Compliance.

9.6 Dynamic Compliance Evaluation

Before implementing an Architecturally Significant Change, the responsible participant or participants shall evaluate whether the proposed modification preserves the applicable Architecture Class.

Dynamic Compliance evaluation shall determine whether the proposed change:

- preserves the defining characteristics of the applicable Architecture Class;
- maintains compliance with all applicable topology rules;
- preserves interoperability;
- maintains mandatory system boundaries;
- supports future scalability;
- avoids Architectural Drift; and
- remains consistent with the governing principles of HOPT-AS.

Where a proposed change cannot preserve these characteristics, the implementation shall no longer be regarded as maintaining Dynamic Compliance until conformity has been restored.

9.7 Continuous Application of Dynamic Compliance

Dynamic Compliance shall apply continuously throughout the lifecycle of a HOPT implementation and shall not be limited to operational infrastructure.

Architecturally significant activities undertaken during strategic planning, master planning, architecture development, engineering design, procurement, construction, commissioning, infrastructure expansion, modification, operation, and long-term stewardship shall be subject to Dynamic Compliance evaluation where such activities may influence the defining characteristics of the applicable HOPT-AS Architecture Class.

Accordingly, Dynamic Compliance provides continuous architectural oversight from the initial conception of a HOPT implementation through its entire operational lifecycle, ensuring that infrastructure blueprints, engineering designs, supplier proposals, technology selections, construction activities, infrastructure modifications, and other architecturally significant decisions remain consistent with the governing principles and requirements of this Standard.

9.8 Architectural Drift

Architectural Drift is the progressive loss of the defining characteristics of an Architecture Class resulting from unmanaged or incompatible infrastructure evolution.

Architectural Drift may occur through a single major modification or through the cumulative effect of multiple individually acceptable changes.

Infrastructure modifications that are locally beneficial shall not be permitted where they undermine the long-term architectural integrity of the overall HOPT implementation.

Preventing Architectural Drift is a fundamental objective of Dynamic Compliance.

9.9 Loss of Architectural Conformance

An implementation shall be regarded as having lost Architectural Conformance where:

- Dynamic Compliance is no longer maintained;
- the defining characteristics of the applicable Architecture Class have been materially altered;
- mandatory topology requirements are no longer satisfied;
- mandatory system boundaries have been violated; or
- Architectural Drift has occurred.

Loss of Architectural Conformance does not necessarily imply engineering failure, operational failure, or regulatory non-compliance.

It signifies only that the infrastructure no longer preserves the Architecture Class defined by HOPT-AS.

9.10 Restoration of Architectural Conformance

Where Architectural Conformance has been lost, conformity with HOPT-AS may be restored only by implementing changes that re-establish Dynamic Compliance with the applicable Architecture Class.

Restoration shall be evaluated on the basis of the current infrastructure configuration rather than solely upon its original design.

9.11 Representation of Conformance

An infrastructure implementation shall be represented as conforming to HOPT-AS only while Dynamic Compliance is maintained.

No participant shall knowingly represent an implementation as conforming to HOPT-AS where Dynamic Compliance has been lost or where Architectural Drift has materially altered the defining characteristics of the applicable Architecture Class.

Claims of conformity shall accurately reflect the current architectural state of the implementation.

9.12 Participant Responsibilities

Dynamic Compliance is a shared responsibility of all participating entities.

Each participant shall:

- perform its activities in accordance with the applicable provisions of HOPT-AS;

- preserve the defining characteristics of the applicable Architecture Class;
- avoid actions likely to result in Architectural Drift;
- cooperate with other participants where necessary to preserve overall architectural integrity; and
- support Dynamic Compliance evaluations relating to activities under its control.

Responsibility for Dynamic Compliance extends throughout the operational lifecycle of the infrastructure and is not limited to the initial implementation phase.

9.13 General Principles of Dynamic Compliance

Dynamic Compliance under HOPT-AS shall be governed by the following principles:

a) Lifecycle Preservation

Architectural Conformance shall be maintained throughout the entire operational lifecycle of the infrastructure system.

b) Architecture Class Integrity

Every implementation shall preserve the defining characteristics of its applicable Architecture Class.

c) Prevention of Architectural Drift

Infrastructure evolution shall preserve long-term architectural integrity rather than optimize only local objectives.

d) Continuous Evaluation

Architecturally Significant Changes shall be evaluated whenever they have the potential to affect the Architecture Class.

e) Shared Responsibility

All participating entities share responsibility for preserving Dynamic Compliance within their respective areas of responsibility.

f) Open Architecture

Infrastructure evolution is encouraged, provided such evolution preserves the governing principles and defining characteristics of HOPT.

g) Long-Term Value Preservation

Dynamic Compliance exists to preserve the long-term interoperability, scalability, resilience, and system-level risk mitigation characteristics that constitute the architectural value of HOPT.

9.14 Conformance beyond physical configuration

Architectural Conformance under HOPT-AS extends beyond the physical configuration of infrastructure and includes continued conformity with the architectural boundaries established in Clause 4.7.

Dynamic Compliance provides the continuous assurance necessary to verify that architecturally significant decisions, infrastructure modifications, supplier proposals, technology substitutions, operational practices, and CO₂ accepted into the HOPT network do not alter the architectural boundaries or invalidate the architectural assumptions upon which the applicable HOPT-AS Architecture Class is established.

Accordingly, Architectural Conformance shall be determined not only by the physical topology of the implementation but also by continued conformity with the architectural boundaries maintained through Dynamic Compliance. Failure to maintain these boundaries may result in the progressive degradation of the system-level risk mitigation characteristics established by this Standard, notwithstanding that the physical infrastructure topology remains unchanged.

SECTION 10 — HOPT-AS CERTIFICATION FRAMEWORK

(Normative)

10.1 Purpose

HOPT-AS establishes a comprehensive certification framework for evaluating, recognizing, and maintaining conformity with the architectural principles, Architecture Classes, and Dynamic Compliance requirements defined by this Standard.

Certification under HOPT-AS is intended to provide independent architectural assurance to governments, regulators, project developers, financiers, insurers, infrastructure owners, engineering organizations, industrial participants, and other stakeholders that a proposed or implemented CCUS system conforms to the applicable requirements of the Hub-Only Pipeline Topology Architecture Standard.

Certification addresses different stages of the infrastructure lifecycle and shall be applied in accordance with the provisions of this Standard.

10.2 Scope of Certification

Certification under HOPT-AS may apply to one or more of the following:

- Regional or national CCUS master plans;
- Infrastructure blueprints and conceptual architectures;
- Front-End Engineering Design (FEED) and project designs;
- Constructed infrastructure systems;
- Operating HOPT implementations;
- Infrastructure expansion and modification proposals;
- Infrastructure portfolios; and
- Other architecturally significant implementations determined by the governing authority of HOPT-AS.

Certification under this Standard evaluates architectural conformity only.

Unless expressly stated otherwise, certification does not constitute approval of engineering design, construction quality, safety performance, operational performance, environmental compliance, financial viability, or regulatory authorization.

10.3 Infrastructure Risk Benchmarking

Typical Stage: *Concept Development, Strategic Planning, Investment Screening and Pre-Feasibility*

Infrastructure Risk Benchmarking evaluates a proposed or existing CCUS architecture against the HOPT-AS architectural benchmark to assess exposure to recognized system-level infrastructure risks and identify opportunities for architectural improvement.

Benchmarking may be performed irrespective of whether the assessed infrastructure seeks certification under HOPT-AS.

Typical beneficiaries include governments, regulators, investors, infrastructure funds, commercial banks, insurance companies, infrastructure owners, and project developers requiring an independent architectural assessment to support planning, investment, financing, underwriting, or strategic decision-making.

Infrastructure Risk Benchmarking provides an independent architectural assessment but does not constitute certification under HOPT-AS.

10.4 Architecture Blueprint Certification

Typical Stage: *Master Planning, Conceptual Design, Feasibility Study and Front-End Architecture Design (FEAD), prior to Front-End Engineering Design (FEED).*

Architecture Blueprint Certification confirms that a proposed CCUS architecture, infrastructure blueprint, or master plan conforms to the applicable HOPT-AS Architecture Class and governing architectural principles prior to implementation.

This certification may be used to support government planning, regional CCUS master plans, investment evaluation, infrastructure financing, project feasibility studies, Front-End Architecture Design, and strategic infrastructure planning.

Typical beneficiaries include governments, Industrial Development Corporations, infrastructure planners, project developers, investors, lenders, infrastructure funds, and regulators evaluating proposed CCUS infrastructure.

Architecture Blueprint Certification evaluates the proposed architecture only and does not certify future implementation.

10.5 Architecture Design Certification

Typical Stage: *Front-End Engineering Design (FEED), Detailed Engineering and Procurement, prior to construction*

Architecture Design Certification confirms that the Front-End Engineering Design (FEED), conceptual engineering, or detailed engineering design of a proposed implementation remains consistent with the certified architectural blueprint and the applicable HOPT-AS Architecture Class.

This certification may be performed during project development, Front-End Engineering Design (FEED), or detailed engineering.

Typical beneficiaries include EPC contractors, engineering consultants, project developers, hub developers, infrastructure owners, and government procurement agencies.

This certification evaluates architectural conformity rather than detailed engineering adequacy. Engineering solutions remain the responsibility of the implementing organization.

10.6 Infrastructure Conformance Certification

Typical Stage: *Construction Completion, Commissioning and Operational Readiness.*

Infrastructure Conformance Certification confirms that an implemented CCUS system conforms to the applicable HOPT-AS Architecture Class following construction or commissioning.

Assessment may include verification of:

- Architectural topology;
- System boundaries;
- Required interfaces;
- Stakeholder responsibilities;
- Permitted infrastructure relationships; and
- Other architecturally significant characteristics defined by this Standard.

Typical beneficiaries include infrastructure owners, hub operators, pipeline operators, storage operators, regulators, financiers, insurance companies, and industrial participants requiring confirmation that implemented infrastructure conforms to HOPT-AS.

10.7 Dynamic Compliance Certification

Typical Stage: *Operational Lifecycle, including routine operation, infrastructure evolution and periodic compliance review.*

Dynamic Compliance Certification confirms that an operational HOPT implementation continues to preserve the defining characteristics of its applicable Architecture Class throughout its operational lifecycle.

Unlike point-in-time certifications, Dynamic Compliance Certification requires continued demonstration that architecturally significant changes remain consistent with the governing principles of HOPT-AS.

Typical beneficiaries include infrastructure owners, hub operators, governments, regulators, investors, long-term infrastructure funds, asset managers, and insurance companies requiring continuing architectural assurance throughout the operational life of the infrastructure.

Maintenance of Dynamic Compliance Certification shall be subject to the Dynamic Compliance and Real-Time Stewardship requirements defined elsewhere in this Standard.

10.8 Expansion and Evolution Certification

Typical Stage: *Prior to implementation of infrastructure expansion, modification, network reconfiguration or integration of new infrastructure.*

Expansion and Evolution Certification evaluates proposed additions, modifications, or reconfiguration of HOPT infrastructure to determine whether such changes preserve the defining characteristics of the applicable Architecture Class.

Evaluation may include:

- Addition of new emitters;
- Addition of regeneration hubs;
- Changes in logistics connectivity;
- Expansion of hub-only pipeline networks;
- Integration of storage or utilization facilities; and
- Other architecturally significant infrastructure changes.

Typical beneficiaries include governments, infrastructure owners, hub operators, pipeline operators, storage operators, and project developers planning phased expansion of HOPT infrastructure.

Certification shall confirm that proposed evolution does not result in Architectural Drift.

10.9 Infrastructure Portfolio Certification

Typical Stage: *Portfolio Planning, Portfolio Acquisition, Multi-Project Governance and Periodic Portfolio Review.*

Infrastructure Portfolio Certification evaluates multiple related CCUS projects, regional developments, or infrastructure assets collectively to determine whether the portfolio maintains architectural consistency with HOPT-AS and supports coherent long-term infrastructure development.

Typical beneficiaries include national and regional governments, Industrial Development Corporations, sovereign wealth funds, infrastructure investment funds, large infrastructure owners, and multi-project developers managing portfolios of CCUS assets.

Portfolio Certification provides a common architectural benchmark across multiple projects and supports consistent long-term investment and infrastructure planning.

10.10 Architectural Assurance

Applicability: *Applies to all benchmarking assessments and certifications issued under HOPT-AS.*

Each certification issued under HOPT-AS provides architectural assurance only.

Certification confirms conformity with the architectural requirements established by this Standard and shall not be interpreted as certifying:

- Engineering adequacy;
- Safety;
- Construction quality;
- Operational performance;

- Regulatory compliance;
- Commercial viability;
- Environmental performance; or
- Patent licensing.

10.11 Relationship Between Certifications

The benchmarking and certifications established by HOPT-AS address different phases of the infrastructure lifecycle.

Benchmarking may be undertaken independently of certification and does not require implementation of HOPT-AS.

Certification at one stage does not automatically confer certification at any subsequent stage.

Where applicable, assessment may progress from Infrastructure Risk Benchmarking through Architecture Blueprint Certification, Architecture Design Certification, Infrastructure Conformance Certification, Dynamic Compliance Certification, and Expansion and Evolution Certification as infrastructure evolves throughout its lifecycle.

10.12 Certification Authority

Official benchmarking and certification under HOPT-AS shall be issued only by Novonanmek Material Sciences Private Limited or by certification bodies expressly authorized by Novonanmek.

Requirements governing benchmarking, certification administration, interpretation, certification marks, registry participation, suspension, withdrawal, renewal, and related administrative matters shall be established by the governing authority of HOPT-AS.

SECTION 11 — GOVERNANCE, UPDATES, AND INTERPRETATION FRAMEWORK

(Normative)

11.1 Purpose

The Hub-Only Pipeline Topology Architecture Standard (HOPT-AS) establishes a governance framework for maintaining the integrity, consistency, interpretation, and controlled evolution of the Standard.

The purpose of this framework is to ensure that HOPT-AS continues to provide a stable architectural foundation for the implementation and long-term preservation of the Hub-Only Pipeline Topology (HOPT), while allowing the Standard to evolve in response to implementation experience, technological advancement, and the changing needs of Carbon Capture, Utilization, and Storage (CCUS) infrastructure.

Governance under HOPT-AS exists to preserve the architectural integrity of the Standard and its Architecture Classes. It governs the interpretation, maintenance, revision, and evolution of the Standard itself and shall not be interpreted as governing the engineering design, commercial operation, ownership, or day-to-day management of individual infrastructure projects.

11.2 Governing Principles

The governance of HOPT-AS shall be guided by the following principles:

a) Preservation of Architectural Integrity

The governing principles of the Hub-Only Pipeline Topology shall remain consistent throughout future revisions of the Standard.

b) Controlled Evolution

HOPT-AS shall evolve in a structured and controlled manner without compromising the defining characteristics of the Hub-Only Pipeline Topology or the integrity of established Architecture Classes.

c) Technical Neutrality

The Standard shall remain independent of specific capture technologies, engineering solutions, equipment manufacturers, commercial arrangements, and regulatory jurisdictions except where such matters directly affect the architectural principles defined by HOPT-AS.

d) Lifecycle Preservation

Governance shall support the continuous preservation of Architecture Classes through Dynamic Compliance throughout the operational lifecycle of HOPT implementations.

e) Consistency

Normative provisions, definitions, Architecture Classes, and Dynamic Compliance requirements shall be interpreted consistently throughout the Standard.

11.3 Maintenance of the Standard

HOPT-AS shall be maintained by Novonanmek Material Sciences Private Limited as the owner and governing authority of the Standard.

Maintenance activities may include:

- publication of revised editions;
- correction of editorial errors;
- clarification of normative provisions;
- refinement of Architecture Classes;
- refinement of Dynamic Compliance requirements;
- addition of explanatory guidance;
- publication of implementation notes; and
- other changes necessary to preserve the technical quality and long-term relevance of the Standard.

Such maintenance activities shall preserve the governing principles of the Hub-Only Pipeline Topology unless expressly stated in a future revision.

11.4 Formal Interpretations

Questions concerning the interpretation or application of HOPT-AS may arise as infrastructure implementations evolve.

Where clarification is required, Novonanmek may issue Formal Interpretations explaining the intended application of the Standard.

Formal Interpretations may clarify:

- Architecture Classes;
- Dynamic Compliance requirements;
- stakeholder responsibilities;
- system boundaries;
- topology requirements;

- definitions;
- terminology; and
- other normative provisions.

Formal Interpretations explain the intended meaning of existing requirements and shall not create new normative requirements except through formal revision of the Standard.

11.5 Revisions

Future editions of HOPT-AS may introduce new Architecture Classes, additional guidance, refined definitions, improved explanatory material, or revised implementation requirements.

Where revisions are published, every effort shall be made to preserve compatibility with the governing principles of previously published editions while allowing the Standard to respond to technological advancement and practical implementation experience.

Revisions shall preserve the fundamental principles of:

- the Hub-Only Pipeline Topology;
- Architecture Classes;
- Dynamic Compliance;
- Architectural Conformance;
- prevention of Architectural Drift; and
- long-term interoperability.

11.6 Dynamic Compliance and Evolution

HOPT-AS recognizes that infrastructure systems evolve continuously throughout their operational lives.

Accordingly, the Standard itself shall evolve in a manner that supports Dynamic Compliance while preserving the defining characteristics of the Hub-Only Pipeline Topology.

The publication of revised editions, updated Architecture Classes, or clarified requirements shall not alter the principle that every HOPT implementation shall preserve Dynamic Compliance with its applicable Architecture Class throughout its operational lifecycle.

11.7 Authority

Novonanmek Material Sciences Private Limited is the originating organization and governing authority for HOPT-AS.

Accordingly, Novonanmek is responsible for:

- maintaining the Standard;
- publishing revisions;

- issuing Formal Interpretations;
- preserving the consistency of Architecture Classes;
- maintaining the integrity of Dynamic Compliance requirements;
- protecting the intellectual integrity of HOPT-AS; and
- supporting the continued evolution of the Standard.

Nothing in this governance framework shall be interpreted as granting Novonanmek authority over the engineering design, ownership, financing, construction, commercial operation, or regulatory oversight of individual infrastructure projects.

11.8 Relationship to Implementations

Governance under HOPT-AS applies to the Standard rather than to individual infrastructure systems.

Individual HOPT implementations remain the responsibility of their respective owners, developers, operators, regulators, and participating stakeholders.

However, where conformity with HOPT-AS is claimed, such implementations shall preserve Dynamic Compliance with the applicable Architecture Class and shall apply the normative provisions of the Standard as published or formally interpreted.

11.9 Future Development

HOPT-AS is intended to evolve as a living architecture standard.

Future revisions may expand the Standard to address new Architecture Classes, emerging technologies, implementation experience, evolving logistics models, additional governance guidance, and other developments relevant to the Hub-Only Pipeline Topology.

Such evolution shall preserve the defining architectural principles of HOPT while ensuring that the Standard remains relevant, technically rigorous, and suitable for long-term infrastructure development

SECTION 12 — GLOSSARY, DEFINITIONS & TERMINOLOGY

(Normative)

This section contains mandatory definitions for all terminology used throughout HOPT-AS. Terms defined here have authoritative meaning across all sections of the standard.

12.1 Core Terms

12.1.1 Hub-Only Pipeline Topology (HOPT)

HOPT is a CCUS architecture in which gaseous CO₂ pipelines connect **only hubs to other hubs and/or storage** and **never connect to emitters**.

Emitters participate exclusively via solids logistics.

12.1.2 HOPT-AS

The Hub-Only Pipeline Topology Architecture Standard (HOPT-AS) - the governed, normative document defining topology rules, boundaries, stakeholder responsibilities, certification, MRV, and compliance.

12.1.3 Architecture

The fundamental organization of an infrastructure system embodied in its components, stakeholder relationships, system boundaries, topology, governing principles, and the rules governing its design, operation, evolution, and interaction with other systems. Within HOPT-AS, architecture defines the structural characteristics through which infrastructure achieves interoperability, scalability, resilience, and long-term system-level performance.

12.1.4 Architectural Conformance

The condition in which an infrastructure implementation continues to preserve the defining characteristics of its applicable Architecture Class through Dynamic Compliance.

12.1.5 Architecturally Significant Change

Any modification capable of altering an Architecture Class, topology, stakeholder relationships, system boundaries, interoperability characteristics, scalability, or other defining architectural characteristics of a HOPT implementation.

12.1.6 Architectural Drift

The progressive loss or alteration of the defining characteristics of an Architecture Class resulting from unmanaged or incompatible infrastructure evolution.

12.1.7 Dynamic Compliance

The continuous preservation of the defining characteristics of the applicable Architecture Class throughout the planning, deployment, operation, expansion, modification, and long-

term evolution of an infrastructure system, ensuring that infrastructure evolution remains consistent with the governing principles of HOPT-AS and preventing Architectural Drift.

12.1.8 Dynamically Preserved Architecture (DPA)

An Architecture Class defined by HOPT-AS whose defining architectural characteristics are continuously preserved throughout the operational lifecycle of the infrastructure system through mandatory Dynamic Compliance.

12.1.9 Licensed Project Initiator (LPI)

An independent, commercially self-sufficient entity or individual chosen and designated by Novonanmek Material Sciences Private Limited, holding a valid, non-transferable commercial license to formally initiate, organize, or register a physical multi-party infrastructure cluster under the HOPT-AS framework at its own expenditure and risk.

12.2 Stakeholder Definitions

12.2.1 Emitter (E)

An Emitter (E) is an industrial facility, industrial campus, process unit, combustion system, furnace, kiln, heater, stack, vent, reactor, process train, or other localized source of carbon dioxide emissions that captures CO₂ in solid-bound form using a HOPT-compliant capture system and participates via solids logistics routes.

An Emitter may comprise:

- a standalone industrial facility,
- an emission source among multiple emission sources within a single industrial facility or industrial campus,
- or one participant within a larger industrial cluster.

12.2.2 Hub (HS)

A Hub (HS) is a centralized regeneration, CO₂ conditioning, compression, and sorbent-cycling facility that interfaces with pipelines and solids logistics systems.

A Hub may serve:

- multiple emitters within a single industrial facility or industrial campus,
- multiple industrial facilities within a geographic cluster,
- or combinations thereof.

The Hub is the exclusive location for gaseous CO₂ regeneration, conditioning, compression, and pipeline interfacing within the HOPT-AS architecture.

12.2.3 Hub Developer / Operator (HD/HO)

Entity that owns, builds, or operates a HOPT hub.

12.2.4 Pipeline Operator (PO)

Pipeline Operator (PO) is the entity responsible for the design, operation, and maintenance of the hub-to-hub CO₂ pipeline system.

12.2.5 Solids Logistics Provider (SLP)

Solids Logistics Provider (SLP) is the entity responsible for transporting CO₂-laden and regenerated solids between emitters and hubs via road, rail, barge, or other logistics modes.

12.2.6 Storage & Utilization Operator (SUO)

Storage & Utilization Operator (SUO) is the entity responsible for receiving pipeline-grade CO₂ and storing or utilizing it under regulatory-approved MRV systems.

12.2.7 Capture Technology Vendor (CTV)

Capture Technology Vendor (CTV) is the entity that supplies and maintains solid-looping CO₂ capture systems compatible with HOPT-AS.

12.3 System Definitions

12.3.1 Emitter System (ES)

Emitter System (ES) consists of all physical and operational components associated with one or more emitters required for:

- solid-bound CO₂ capture,
- temporary solids storage,
- solids handling,
- and logistics interfacing within a HOPT-AS architecture.

An Emitter System may correspond to:

- a single emission source,
- an emission source among multiple emission sources within a single industrial facility,
- or one or more emitters participating within a larger industrial cluster.

12.3.2 Solids Logistics System (SLS)

All systems, processes, vehicles, and containers used to transport solids between emitters and hubs, including external logistics systems and internal industrial solids-transfer systems.

12.3.3 Hub System (HS)

The Hub System (HS) consists of all systems and operational components associated with centralized:

- sorbent regeneration,
- gaseous CO₂ release,
- gas conditioning,
- compression,
- solids intake and output,
- and pipeline interfacing within a HOPT-AS architecture.

A Hub System may serve:

- distributed emitters within a single industrial facility,
- multiple emitters across an industrial cluster,
- or multiple interconnected HOPT deployment zones.

The Hub System remains the sole location for pipeline-grade gaseous CO₂ handling within the HOPT-AS topology.

12.3.4 Pipeline System (PS)

The Pipeline System (PS) consists of all gaseous CO₂ pipelines, compression stations, metering stations, SCADA, and branching nodes connecting hubs to hubs or storage.

12.3.5 Storage & Utilization System (SUS)

Systems responsible for the long-term storage or industrial utilization of CO₂ delivered via pipelines.

12.4 MRV Terms

12.4.1 Chain-of-Custody (CoC)

A continuous and auditable record of custody transfers from emitter → logistics → hub → pipeline → storage.

12.4.2 MRV (Measurement, Reporting, Verification)

The framework ensuring accurate carbon accounting, mass balance, and compliance

12.4.3 Batch Identification (Batch ID)

A unique digital identifier assigned to solids containing CO₂.

12.5 Topology Terms

12.5.1 Topology Class

A predefined, governed architecture family describing allowed hub–emitter–pipeline arrangements.

12.5.2 Non-Compliant Topology

Any system that violates HOPT mandatory rules or boundaries

SECTION 13 — SAFETY & REGULATORY CONSIDERATIONS

(Informative)

This section provides guidance (not mandatory rules) on safety and regulatory considerations relevant to HOPT deployments.

13.1 Purpose

Safety and regulatory compliance are fundamental to CCUS projects. While HOPT-AS defines architecture, it does not replace national regulations, pipeline codes, or safety standards.

This section highlights relevant considerations for stakeholders.

13.2 Emitter Safety Considerations

13.2.1 Solid-Looping Materials Safety

Emitters must ensure safe handling of:

- CaO/CaCO₃ or equivalent materials,
- Thermal management of capture units,
- Solids containment during storage and transport.

13.2.2 On-Site Storage

Solids storage at emitters must comply with:

- Local fire/explosion codes,
- Occupational safety guidelines,
- Material-handling regulations.

13.3 Logistics Safety Considerations

- Transport containers must be sealed and spill-resistant.
- Vehicles must comply with hazardous-material transport rules (if applicable).
- Logistics routes must be planned with community risk assessments.

13.4 Hub Safety Considerations

13.4.1 Regeneration Units

Regeneration involves high-temperature reactors; safety must follow:

- Process safety standards (IEC/ISO),
- Thermal runaway prevention,
- Emergency shutdown systems.

13.4.2 CO₂ Conditioning and Compression

Must follow:

- ASME pressure vessel codes,
- API/DNV pipeline gas standards,
- Occupational safety requirements for gas handling.

13.5 Pipeline Safety Considerations

Pipeline safety is governed by:

- ASME B31.4 / B31.8 (or local equivalents),
- DNV-GL CO₂ pipeline guidelines,
- Local/state pipeline safety authorities.

HOPT imposes additional constraints:

- No emitter tie-ins,
- Hub-to-hub only,
- Controlled injection nodes.

13.6 Storage Safety Considerations

Storage operators must comply with:

- National CCS regulations,
- Subsurface pressure management rules,
- Leakage monitoring and reporting.

13.7 Regulatory Harmonization

HOPT-AS deployments should seek alignment with:

- National CCUS legislation,
- Carbon-crediting methodologies,
- Air pollution control standards,
- Industrial permitting frameworks,
- Pipeline and logistics permitting systems.

Novonanmek may issue region-specific regulatory addendums.

SECTION 14 — INFORMATIVE ANNEXES

(Non-normative)

This section contains **informative (non-normative) annexes** provided to support understanding, adoption, and contextual interpretation of the Hub-Only Pipeline Topology Architecture Standard (HOPT-AS). Annexes may be issued, updated, or expanded separately by Novonanmek without requiring revision of the core standard.

The annexes in this section are **not mandatory** and **do not introduce requirements, obligations, eligibility conditions, or certification criteria**. They are intended to assist stakeholders—including industrial participants, regulators, financiers, policymakers, and technical reviewers—in understanding the rationale, value proposition, and practical context of the HOPT architecture.

In the event of any inconsistency between an informative annex and a normative section of this standard, **the normative sections shall prevail**.

14.1 Purpose of the Informative Annexes

The informative annexes serve the following purposes:

- To explain the **motivation and background** behind the development of HOPT-AS;
- To provide **plain-language descriptions** of the HOPT topology and its operational logic;
- To illustrate the **strategic, regulatory, and economic context** in which HOPT-AS is intended to be deployed;
- To describe **stakeholder value and adoption benefits** without creating binding commitments;
- To support **policy alignment, funding evaluation, and market understanding** while remaining adaptable to evolving regulatory and financial frameworks.

14.2 Structure of Informative Annexes

The informative annexes of HOPT-AS may include, but are not limited to, the following categories:

- **Annex A: Integration Pathways for Diverse Carbon Capture Technologies**
This annex provides guidance on how diverse carbon capture technologies—including but not limited to liquid chemical absorption (e.g., amine-based scrubbing), physical solvents, membrane separation, cryogenic capture, and Direct Air Capture (DAC)—can fulfill the interface requirements to achieve compliance and vetting under the Hub-Only Pipeline Topology Architecture Standard (HOPT-AS).
- **Annex B — Energy Infrastructure Architecture Program (EIIP)**
A 4 Phase Implementation and Governance Program for Dynamically Preserved Architectures

- **Annex C — Origin and Development of HOPT-AS**
Summarises the background, research basis, and real-world deployment considerations that informed the development of the HOPT architecture standard.
- **Annex D — Topology Overview and Operational Model (Informative)**
Provides a descriptive, non-technical explanation of the Hub-Only Pipeline Topology, including solids-based capture, centralized regeneration at hubs, and hub-to-hub pipeline connectivity.
- **Annex E — Policy, Funding, and Market Alignment Context**
Explains how HOPT-AS aligns with emerging CCUS policy frameworks, infrastructure planning approaches, climate finance mechanisms, and carbon market expectations, without asserting eligibility or endorsement.

Additional informative annexes may be introduced in future revisions of this standard to reflect deployment experience, regulatory evolution, or stakeholder feedback.

14.3 Non-Normative Status

The informative annexes:

- Do **not** alter or override topology rules defined in Sections 2, 4, or 5;
- Do **not** modify stakeholder responsibilities defined in Section 3;
- Do **not** affect participation eligibility or certification requirements defined in Section 6;
- Do **not** constitute regulatory approval, financial qualification, or carbon credit eligibility.

Their role is explanatory and contextual only.

14.4 Single Site Distributed Emitter Deployments

HOPT-AS may be applied within a single industrial facility containing multiple distributed emission sources. In such deployments:

- multiple emitter nodes may operate within one industrial campus,
- centralized regeneration may occur within the same facility boundary,
- internal solids logistics systems may replace external logistics systems,
- and the centralized hub remains the sole location for gaseous CO₂ handling and pipeline interaction.

Such deployments remain fully consistent with the Hub-Only Pipeline Topology principles defined by this Standard.

14.5 Future Expansion

As HOPT-AS adoption progresses, future versions of this standard may expand the informative annexes to include illustrative examples, deployment narratives, or clarifications derived from implementation experience. Such additions will remain non-normative unless explicitly reclassified through a formal revision of the standard.

14.6 Closing Statement

The informative annexes complement the normative core of HOPT-AS by providing context, clarity, and interpretive guidance. Together, they support consistent understanding and confident adoption of the Hub-Only Pipeline Topology while preserving the architectural integrity and governance discipline of the standard.

No system, entity, or deployment may claim compliance with the Hub-Only Pipeline Topology Architecture Standard unless it satisfies all applicable requirements of this document and holds valid certification or registry status issued under the authority defined herein.

This section constitutes the final normative provision of HOPT-AS.

No requirements are defined beyond this point.

References

1. Chauhan, S., & Sinha, A. *A Novel Pipeline Configuration for Carbon Dioxide Transportation*. Indian Patent Application No. **202531094896**, filed **02 October 2025**.
2. Sinha, Arnab, *A National Framework for Public Good: The Hub-Only Pipeline Topology (HOPT) for Carbon Dioxide Capture & Transportation* (October 15, 2025). Available at SSRN: <https://ssrn.com/abstract=5608430> or <http://dx.doi.org/10.2139/ssrn.5608430>

ANNEX A: INTEGRATION PATHWAYS FOR DIVERSE CARBON CAPTURE TECHNOLOGIES

(Informative – Non-Normative)

A.1 Purpose and Scope

This annex provides guidance on how diverse carbon capture technologies—including but not limited to liquid chemical absorption (e.g., amine-based scrubbing), physical solvents, membrane separation, cryogenic capture, and Direct Air Capture (DAC)—can fulfill the interface requirements to achieve compliance and vetting under the Hub-Only Pipeline Topology Architecture Standard (HOPT-AS).

Because HOPT-AS is a system architecture and transport standard rather than a chemical process standard, it remains entirely agnostic to the internal engineering of the capture facility. Compliance is strictly evaluated based on the physical state, safety profile, and data-logging boundaries of the carbon mass as it crosses the Emitter Property Line.

A.2 The General Compliance Principle: Boundary Conditioning

HOPT-AS does not require an emitter to use a specific solid-looping capture chemistry inside their plant. Instead, it requires the emitter to install an **Interface Configuration Module** at their gate. This module acts as a "packaging unit" that transforms the output of any capture technology into an inert, transportable solid matrix that satisfies a defined HOPT-AS Emitter Class.



A.3 Specific Technology Mapping Examples

A.3.1 Liquid Solvent Systems (e.g., Amine-Based Chemical Scrubbing)

1. **The Capture Process:** Traditional liquid amine systems use an absorber column to capture CO₂ from flue gas and a stripper column to thermally release pure, low-to-medium-pressure gaseous CO₂.
2. **The HOPT-AS Friction Point:** In a conventional CCUS model, the developer would be forced to deploy heavy multi-stage compressors, dehydration units, and cryogenic refrigeration to turn this gas into a high-pressure supercritical fluid suitable for a localized pipeline network.

3. **The HOPT-AS Alignment Pathway:** Under HOPT-AS, instead of routing the hot, low-pressure gas from the stripper column into a compressor stack, it is routed into an ambient-pressure solidification or mineralization reactor at the factory gate. The gaseous CO₂ is reacted inline with alkaline industrial byproducts (e.g., steel slag, fly ash, or crushed calcium/magnesium silicates) to fix the carbon into stable, non-hazardous solid mineral carbonates (such as synthetic limestone or dolomite).
4. **Investibility Advantage:** The developer avoids the intense capital expenditure (CapEx) of high-pressure compression and localized pipeline permitting. The high-energy requirement of liberating and compressing the gas for permanent storage is completely outsourced to the Centralized Regional Hub, lowering localized plant risk.

A.3.2 Membrane and Cryogenic Separation Systems

1. **The Capture Process:** These systems rely on physical barriers or intense cooling to separate CO₂ from flue gas, typically resulting in a concentrated stream of gaseous CO₂ at various pressures.
2. **The HOPT-AS Alignment Pathway:** Similar to solvent systems, the concentrated gaseous stream is directly fed into an absorption matrix or a temporary chemical binding solid carrier system at the facility's exit boundary.
3. **Investibility Advantage:** Eliminates the necessity of synchronizing factory operations with a rigid regional pipeline network. If the membrane system experiences an unexpected maintenance shutdown, no pressure shocks are sent down a public pipeline network; the logistics fleet simply pauses truck dispatches.

A.3.3 Direct Air Capture (DAC) Systems

1. **The Capture Process:** DAC technologies utilize ambient air contactors containing solid sorbents or liquid solvents to trap ultra-dilute atmospheric CO₂, which is then desorbed using thermal or electrical energy.
2. **The HOPT-AS Alignment Pathway:** DAC developers can bypass the complex, multi-year process of siting their direct-air contactors near deep geological storage wells or main pipeline trunks. By passing their desorbed gas into a localized HOPT-AS solid-matrix packaging module, they can site DAC contactors anywhere with optimal renewable energy profiles (such as isolated solar or geothermal pockets) and use standard truck or rail infrastructure to move the captured solid mass to a regional gathering hub.

A.4 Summary Vetting Criteria for All Emitters

To pass a HOPT-AS technical due diligence audit for investment screening, an emitter utilizing *any* core capture technology must satisfy the following four gateway questions:

1. **Gaseous Boundary Isolation:** Does hazardous, high-pressure gaseous CO₂ cross the property boundary? (*Requirement: No. The carbon must cross the boundary bound into an inert solid form or low-risk ambient carrier*).

2. **Standardized Class Conformance:** Does the final physical output (granular aggregate, powder, or block) comply perfectly with the particle size, moisture limits, and chemical purity metrics of an authorized HOPT-AS Emitter Class? (*Requirement: Yes*).
3. **Logistics Independence:** Can the facility operate and export its captured carbon utilizing standard bulk freight networks (road, rail, or maritime) without demanding an active pipeline connection on Day 1? (*Requirement: Yes*).
4. **Registry Verification:** Is the exit gate instrumented with calibrated mass balancing and continuous logging sensors that interface directly with the HOPT-AS Dynamic Compliance Registry? (*Requirement: Yes*).

A.5 Conclusion

HOPT-AS acts as a universal vetting tool for infrastructure finance precisely because it evaluates **the transfer of risk, liability, and physical state at the system boundary**, rather than the internal chemical engineering of the capture facility. Any carbon capture technology can achieve certified compliance and unlock hub-aggregated project financing by ensuring its exit interface delivers a standardized, low-risk solid unit.

ANNEX B: ENERGY INFRASTRUCTURE IMPLEMENTATION PROGRAM (EIIP)

B.1 Purpose

The **Energy Infrastructure Implementation Program (EIIP)** is the long-term implementation, governance, capital alignment, and stewardship framework developed by Novonanmek for architecture-governed infrastructure ecosystems.

Within the context of HOPT-AS, EIIP provides the institutional framework through which the principles of **Dynamic Compliance**, **Real-Time Stewardship**, **Architecture Assurance**, and **Lifecycle Governance** are implemented throughout the operational life of a Hub-Only Pipeline Topology (HOPT) infrastructure ecosystem.

While HOPT-AS defines *what* constitutes architectural compliance, EIIP establishes *how* architectural integrity is preserved as infrastructure is financed, developed, expanded, operated, and evolved over multiple decades.

B.2 Relationship with HOPT-AS

HOPT-AS and EIIP perform complementary but distinct functions.

HOPT-AS establishes:

- The architecture;
- The topology rules;
- Dynamic compliance requirements;
- Governance principles;
- Architecture assurance requirements; and
- Certification and conformance requirements.

EIIP establishes the institutional implementation environment within which those requirements are continuously applied throughout the infrastructure lifecycle.

Accordingly:

HOPT-AS defines the Standard. EIIP operationalizes the Standard.

B.3 EIIP and Dynamic Compliance

Dynamic Compliance is a foundational principle of HOPT-AS.

EIIP provides the institutional processes through which Dynamic Compliance is exercised throughout planning, capital deployment, infrastructure delivery, operation, expansion, and long-term ecosystem evolution.

Through EIIP, proposed infrastructure developments are continuously evaluated against the approved Architecture Blueprint to preserve the defining architectural characteristics of the Hub-Only Pipeline Topology and to prevent Architectural Drift.

Accordingly, EIIP serves as the operational implementation framework supporting Dynamic Compliance within HOPT-AS.

B.4 Lifecycle Overview

EIIP is implemented through four sequential phases:

Phase	Purpose
Phase 1	Architecture Qualification and Blueprint Development
Phase 2	Capital Mobilization and Ecosystem Formation
Phase 3	Infrastructure Delivery and Implementation Governance
Phase 4	Dynamic Compliance, Real-Time Stewardship and Ecosystem Evolution

Together these phases provide a continuous governance pathway extending from architecture development through long-term infrastructure stewardship.

B.5 Scope of EIIP

EIIP is architecture-agnostic.

Although referenced within HOPT-AS, the framework may also support other architecture-governed infrastructure ecosystems where Dynamic Compliance and long-term architecture preservation are required.

Examples include:

- Carbon Capture, Utilization and Storage (CCUS);
- Hydrogen Infrastructure;
- Nuclear-enabled Industrial Infrastructure;
- Regional Energy Infrastructure;
- Strategic Infrastructure Corridors; and
- other architecture-governed infrastructure ecosystems.

B.6 Status

EIIP is a proprietary implementation and stewardship framework developed by Novonanmek.

This Annex is provided solely to explain the relationship between HOPT-AS and EIIP.

The detailed methodologies, governance procedures, implementation processes, operational practices, institutional arrangements, and supporting documentation comprising EIIP are maintained independently by Novonanmek and are outside the scope of this Standard.