

The Architecture of Durable Infrastructure

Seven Fundamental Truths, the Ten-Fold Path and Architectural Benchmarks for CCUS and Hydrogen

The development of CCUS and hydrogen infrastructure is often considered one project, one investment or one asset at a time. Yet these infrastructures will ultimately operate as regional systems, bringing together multiple participants, assets, technologies and pathways over decades. The challenge is therefore not simply to build infrastructure that works today, but to create systems that can attract and accommodate multiple participants, evolve as circumstances change, expand without fundamental redesign, and preserve their value as they grow.

This requires us to begin with a small number of fundamental truths about how such infrastructure systems develop. These truths establish **why a system architecture is necessary**, what it must enable, and what risks it must prevent. From them follows a **Ten-Fold Path**—the characteristics that a durable infrastructure system should demonstrate. The Path then leads to the need for an **Architectural Benchmark**: an objective reference against which those characteristics can be assessed and assured throughout the infrastructure lifecycle.

The journey therefore moves from Truth, to Path, to Benchmark—and ultimately to the frameworks that make the benchmark applicable to CCUS and hydrogen infrastructure.

The Seven Fundamental Truths

Truth 1 — Durable infrastructure requires a regional, multi-stakeholder system.

CCUS and hydrogen infrastructure developed around a single project, producer, emitter, user or counterparty can create concentration, utilisation and stranded-asset risks. A regional system brings together multiple participants and infrastructure requirements, allowing capacity and investment to be shared across a broader base.

Such systems can diversify participation, improve utilisation and create stronger conditions for long-term infrastructure bankability and investment.

A durable infrastructure system must be designed for multiple stakeholders, not built around a single project or counterparty.

Truth 2 — Project success does not guarantee system success.

An individual project can be technically sound, commercially viable and successfully commissioned, yet still contribute to a fragmented or inefficient infrastructure system. When

projects are developed independently, they may create duplication, incompatible connections, under-utilised capacity or constraints on future development.

The success of each component therefore needs to be considered in the context of the system it forms part of.

Successful projects do not automatically create a successful infrastructure system.

Truth 3 — The future composition of the system cannot be known with certainty.

CCUS and hydrogen infrastructure will evolve over decades. New emitters, producers, users, storage destinations, hubs, logistics pathways and markets will emerge, while existing participants and requirements will change.

Infrastructure designed only around today's participants may therefore become constrained as the system develops.

Infrastructure must be capable of accommodating participants, requirements and pathways that cannot yet be fully known.

Truth 4 — Shared infrastructure can be more effective than isolated infrastructure.

Where infrastructure can serve multiple participants, it can reduce duplication, improve utilisation and reduce dependence on individual projects or counterparties. Shared hubs, corridors, pipelines and logistics infrastructure can also provide a foundation for subsequent participants to enter the system.

The objective is therefore not simply to connect individual projects, but to create infrastructure that can be used and expanded by a wider community of participants.

Shared infrastructure can turn individual project requirements into a more efficient and resilient regional system.

Truth 5 — Infrastructure must be capable of progressive expansion without fundamental redesign.

Regional CCUS and hydrogen systems will not be built in their final form from the outset. Capacity, participants, hubs, pipelines, logistics pathways, storage destinations and demand will develop progressively.

The infrastructure established in the early stages must therefore provide a foundation for subsequent growth rather than becoming a constraint on it.

Today's infrastructure must create the platform for tomorrow's expansion.

Truth 6 — Independently developed infrastructure must be capable of operating as one system.

No single organisation is likely to develop every component of a regional CCUS or hydrogen infrastructure system. Different participants will make investment decisions at different times and under different technical, commercial and regulatory circumstances.

For the resulting infrastructure to function as a coherent system, independently developed assets must be capable of connecting, interacting and expanding together.

Independent development must not lead to incompatible infrastructure.

Truth 7 — The architecture must remain coherent as the infrastructure evolves.

Establishing an appropriate architecture at the beginning is not sufficient. New participants will connect, assets will be expanded or modified, new hubs and pathways will emerge, and existing infrastructure may change its role.

Individual decisions may appear reasonable while collectively causing the system to drift away from its original architectural intent.

The defining characteristics of the infrastructure system must be preserved throughout its lifecycle.

The Ten-Fold Path

The Ten-Fold Path provides the corresponding characteristics through which these fundamental problems can be addressed.

1. System Coherence

Develop infrastructure as components of a coherent system rather than as isolated projects.

2. Aggregated Participation

Design infrastructure to accommodate multiple emitters, producers, users and other participants.

3. Shared Infrastructure

Maximise the practical use of common hubs, corridors, pipelines, logistics and supporting infrastructure.

4. Diversified Participation

Reduce structural dependence on individual emitters, producers, users, offtakers, storage destinations or pathways.

5. Interoperability

Enable independently developed infrastructure to integrate into a common regional or national system.

6. Progressive Scalability

Enable infrastructure to expand incrementally without fundamental redesign of the underlying architecture.

7. Flexibility and Optionality

Preserve the ability to accommodate changing participants, technologies, markets, destinations and pathways.

8. Network Formation

Ensure that individual developments contribute to the progressive formation of larger, interconnected infrastructure networks.

9. Lifecycle Architectural Integrity

Preserve the defining characteristics of the architecture throughout infrastructure development, operation, expansion and modification.

10. Continuous Assurance

Provide an objective basis for assessing and demonstrating that the required architectural characteristics remain present throughout the infrastructure lifecycle.

The Architectural Benchmark

The Ten-Fold Path defines the characteristics that a durable CCUS or hydrogen infrastructure system should demonstrate.

The next question is:

How can these characteristics be defined consistently, assessed objectively and preserved throughout the infrastructure lifecycle?

The **Architectural Benchmark** provides that reference.

It establishes a common basis for assessing whether infrastructure:

- Forms part of a coherent system;
- Supports multiple participants;
- Uses shared infrastructure effectively;
- Avoids excessive concentration and dependency;
- Remains interoperable;
- Can scale without fundamental redesign;
- Preserves future flexibility and optionality;
- Contributes to wider network formation; and
- Maintains its defining architectural characteristics as it evolves.

The benchmark therefore moves these characteristics from **principles to assessable requirements**.

It does not replace conventional engineering, financial, legal, environmental or commercial due diligence.

Rather, it addresses a complementary question:

Will the infrastructure architecture remain coherent, interoperable, scalable and capable of preserving long-term infrastructure value as the wider system evolves?

The benchmark can therefore provide a basis for **assessment, conformance and lifecycle assurance** rather than simply point-in-time project approval. This is consistent with the source frameworks' distinction between conventional project due diligence and architectural assessment.

The Two Architectural Frameworks

The Architectural Benchmark is applied through two sector-specific frameworks.

HOPT-AS — CCUS

Hub-Only Pipeline Topology Architecture Standard

HOPT-AS provides an architectural and assurance framework for CCUS infrastructure.

It establishes a system architecture in which emitters, hubs, logistics pathways, pipelines, storage and utilisation infrastructure can participate in a progressively expanding network.

Its purpose is to address recognised infrastructure risks including:

- Infrastructure fragmentation;
- Duplication;
- Under-utilisation;
- Stranded infrastructure;
- Constrained future expansion;
- Interoperability challenges; and
- Architectural drift.

The framework supports **multi-emitter, multi-hub and multi-storage/utilisation development**, with progressive capital deployment and lifecycle assurance.

Its defining characteristic is that the architecture is not simply established at inception; it is **dynamically preserved as the CCUS system evolves**.

HLAS — Hydrogen

Hydrogen Logistics Architecture Standard

HLAS provides an architectural and assurance framework for hydrogen logistics infrastructure.

It establishes architectural principles addressing:

- Aggregated demand;
- Diversified offtake;
- Shared infrastructure;
- Production consolidation;
- Scalability;
- Interoperability;
- Export optionality;
- Network formation; and
- Long-term bankability

The framework is intended for an open and evolving infrastructure system in which production, logistics, demand, storage, export and supporting infrastructure can be added, expanded, modified, retired or reconfigured over time.

Its purpose is to enable independently developed infrastructure to form **coherent regional and national hydrogen logistics systems** while preserving scalability, interoperability and long-term adaptability.

The Complete Logic

Seven Fundamental Truths

What can go wrong in infrastructure deployment?



Ten-Fold Path

What characteristics should a durable infrastructure system demonstrate?



Architectural Benchmark

How can those characteristics be defined, assessed and assured?



HOPT-AS + HLAS

The sector-specific architectural benchmark frameworks for CCUS and hydrogen logistics

A clean progression:

- **The Truths establish the need.**
 - **The Path establishes the characteristics.**
 - **The Benchmark makes those characteristics assessable.**
- HOPT-AS and HLAS provide the frameworks through which they can be assessed and preserved.**

Download:

1. HOPT-AS: <https://ssrn.com/abstract=6143086>
2. HLAS: <https://ssrn.com/abstract=6667160>