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Global CCUS System Architecture Benchmark: The Hub-Only Pipeline Topology Architecture Standard (HOPT-AS)

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Abstract

Traditional Carbon Capture, Utilization, and Storage (CCUS) infrastructure planning relies heavily on centralized, linear pipeline networks. These models expose institutional investors to prohibitive asset stranding, cross-chain default liabilities, and unmitigated single-point-of-failure (SPOF) risks. This paper presents a structural evolution framework that systematically minimizes investment and operational risks by shifting from rigid linear configurations to a decentralized, modular mesh network. By stripping away the conventional "trunk pipeline" and leveraging structural mirror symmetry, we introduce a repeatable framework: the **Hub-Only Pipeline Topology Architecture Standard (HOPT-AS)**, also designated as Case (ii) or the Standardized Architecture Module (SAM).

We topologically demonstrate that **Case 0 (the bare pipeline segment)** functions as the atomic building block of this framework, and that all alternative regional architectures are combinations that fit natively inside it. This paper maps a direct, stepwise evolution from this bare asset to the ultimate minimum-risk baseline, establishing a definitive standard for institutional project finance in macro-regional decarbonization.

1. Introduction & The Institutional Investor Problem

The widespread deployment of large-scale CCUS is fundamentally stalled by commercial project finance constraints and unmitigated Architectural Risk. Capital-heavy trunk pipelines require absolute, long-term cross-chain certainty: industrial emitters must consistently capture volume, and deep geological sinks must consistently absorb it. If an anchor emitter defaults or a primary injection well faces an abrupt regulatory or geological halt, the unyielding physical connection turns the entire pipeline corridor into an unrecoverable, multi-million-dollar stranded asset.

Institutional lenders view traditional emitter-connected pipeline architectures as a high-risk, single-engine dependency where any isolated failure along the value chain defaults the entire enterprise. Furthermore, real-world execution faces severe multi-jurisdictional permitting barriers, high upfront capital costs for site-specific compression/dehydration, and extreme friction when onboarding small-to-medium enterprises (SMEs).

To overcome these boundaries, this paper develops a risk-reduction trajectory starting from a non-functional asset up to a universally applicable, low-risk architectural benchmark. This benchmark is formalised under the **Hub-Only Pipeline Topology Architecture Standard (HOPT-AS)**. HOPT-AS establishes a family of Dynamically Preserved Architectures

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(DPAs) that provide an aviation-grade "twin-engine" safety standard, ensuring that localized counterparty shocks or volumetric fluctuations are dynamically balanced out by an open, interconnected grid topology.

2. The Stepwise Architectural Evolution (Cases 0 to 3)

To isolate architectural variables and track risk mitigation mechanics, the framework begins with a bare, baseline pipeline asset and progressively builds functionality step-by-step.

Case 0: The Isolated Trunkline (Absolute Capital Loss)

- **Topology:** A standalone pipeline segment with zero connected emitters and no Sink/Utilization (S/U) endpoints.
- **Evolutionary Baseline:** This is the absolute atomic denominator of the framework—a bare piece of buried steel.
- **Risk Profile: 100% Stranded Asset.** The debt service coverage ratio (DSCR) is zero; capital is entirely trapped in non-functional, unrecoverable capital.

Case 1: Simple Binary Link (Transition from Case 0)

- **Evolutionary Step:** Case 0 becomes Case 1 by **adding exactly one dedicated emitter** at the source end and **one dedicated sink/utilization point** at the destination end.
- **Risk Shift:** Risk reduces from the total loss of Case 0 because an active operational and commercial pathway now exists. However, it introduces **High Binary Risk**. The architecture suffers from a complete lack of optionality; if either single facility goes offline, network revenue instantly hits zero.

Case 2: Source Aggregation (Transition from Case 1)

- **Evolutionary Step:** Case 1 evolves into Case 2 by **adding more emitters** on the source side to converge into a centralized hub, and **adding more sinks/utilization sites** on the destination side to create a disposal cluster.
- **Risk Shift:** Risk reduces further due to volume diversification. If one factory suffers an operational halt, the remaining aggregated factories maintain volume. However, this configuration introduces a massive **Backbone Bottleneck**. The central trunk pipeline remains an unmitigated physical and financial Single Point of Failure (SPOF). A single leak or regulatory freeze along this line strands the entire asset.

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Case 3: Upstream Decoupling (Transition from Case 2)

- **Evolutionary Step:** Case 2 evolves into Case 3 by **decoupling the emitters from the pipeline network**. Instead of using localized feeder pipes to reach the hub, carbon is captured in solid-bound form using solid-looping technologies. These carbon-laden solids are moved to the hub via flexible **solid logistics** (rail, truck, or barge), where the hub gasifies the CO_2 and pumps it into the main trunkline.
- **Risk Shift:** Upstream stranded asset risk drops drastically. Emitters can alter operational capacity or face insolvency without leaving behind dead, buried feeder pipe steel—vehicular transport assets are simply rerouted. However, the downstream trunk pipeline itself remains fully exposed to absolute stranding if the final disposal cluster fails.

3. Eliminating the Trunkline & the Mirror Symmetry

The core breakthrough of this framework occurs when we challenge the necessity of a dedicated trunk pipeline. By removing it entirely, we transition from rigid linear transport to an open network. When the central trunkline is deleted, a structural **mirror symmetry** emerges.

This transformation is executed by passing an imaginary **mirror line directly through the downstream S/U sites**. By duplicating the architecture across this mirror axis, the dead-end pipeline destination is transformed into a central balancing bridge that loops two distinct regional hubs together. Under this spatial rule, **Case (i)** is created by establishing the mirror image of **Case 2**, while **Case (ii)** is created by establishing the mirror image of **Case 3**.

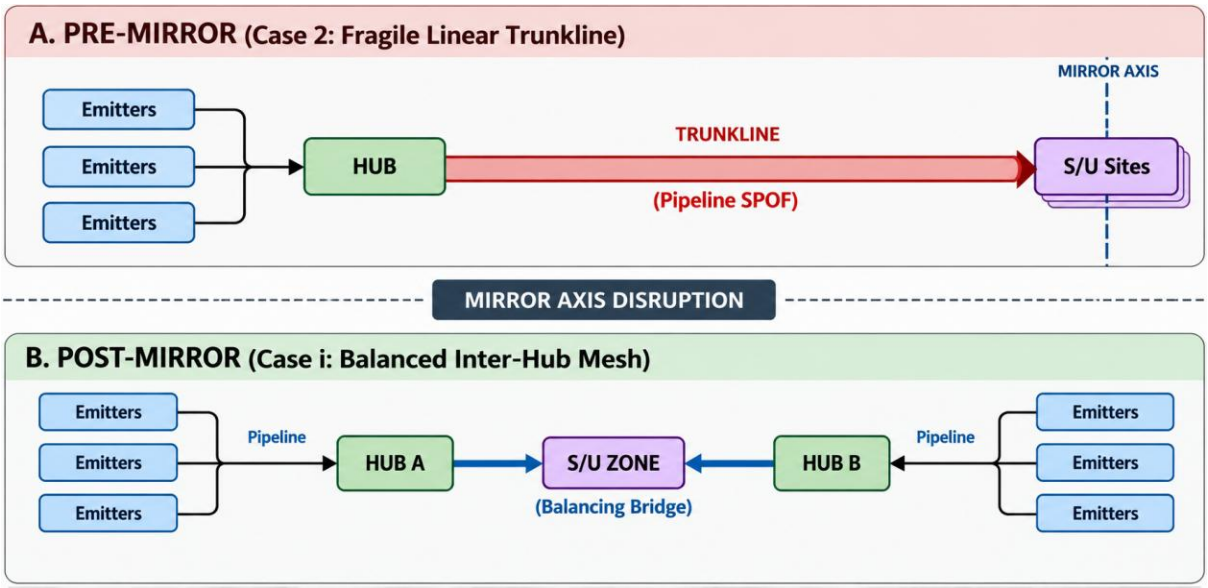


Figure 1: The Mirror Disruption Paradigm Shift.

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Case (i): The Inter-Hub Pipeline Mesh Grid (The Mirror of Case 2)

- **Topology:** Case (i) is created by generating the **spatial mirror image of Case 2** across the S/U mirror axis. The centralized trunkline is completely eliminated. Pipelines are laid strictly to connect **Hub A to Hub B**, forming an open loop where the pipeline bridge acts as a balancing pool. The S/U sites sit in the center of this bridge. Emitters connect to the hubs using traditional local feeder pipelines.
- **Risk Shift:** The moment this mirror symmetry is established, systemic risk drops dramatically. Because the central S/U zone is now backed by a twin-engine hub configuration, **overall failure risk is slashed by roughly 50% to 60%** compared to Case 2. Downstream trunkline stranding risk is eliminated because the pipeline bridge is supported by two separate hub economies. If Hub A faces a major supply shock, Hub B dynamically reverses the direction of flow to keep the central S/U sites operating seamlessly. However, upstream pipeline capital exposure at the emitter boundary remains active.

Case (ii): The HOPT-AS / SAM Benchmark Architecture (The Mirror of Case 3)

- **Topology:** Case (ii) is created by generating the **spatial mirror image of Case 3** across the S/U mirror axis. It applies the solid logistics principle from Case 3 to both sides of the mirrored network. Emitters on both sides are completely decoupled from the hubs, using flexible vehicular/vessel transport to drop off solid carbon carriers at Hub A and Hub B.
- **Risk Shift: Theoretical Minimum Risk Floor.** By combining full mirror symmetry with complete logistical decoupling, **systemic asset stranding and counterparty risks drop by roughly 85% to 90%** relative to the original linear models. This configuration establishes the formal **Hub-Only Pipeline Topology Architecture Standard (HOPT-AS)**, also designated as the Standardized Architecture Module (SAM). It strips away all physical pipeline exposure from emitter boundaries, leaving the central balancing bridge as the sole pipeline asset in operation.

4. Why HOPT-AS is the Definitive CCUS Benchmark

Universality via Topological Decomposition

HOPT-AS functions as the definitive baseline because it serves as the master set that completely subsumes all other architectures. Under this framework, **Case 0 (the isolated pipeline segment)** is recognized as the fundamental atomic building block of infrastructure. Every alternative architecture, phased project extension, or regional combination can be broken down into a series of individual Case 0 components that fit cleanly within the boundaries of the master HOPT-AS module. This makes the benchmark universally applicable to any regional configuration.

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The "Twin-Engine" Safety Advantage

The HOPT-AS framework operates exactly like a twin-engine commercial airplane. For the central storage asset to lose its carbon supply and fail, **both Hub A and Hub B must undergo catastrophic, simultaneous system failures.** If a single hub carries a 10% failure probability ($P = 0.10$), the multi-hub network slashes systemic asset starvation risk down to 1% ($0.10 x 0.10 = 0.01$). This architectural duplication unlocks the lowest achievable risk floor for institutional capital.

Purity and Pressure Liability Isolation

By preventing emitters from injecting gas directly into pipelines, cross-contamination, corrosion, and multi-party phase-behavior liabilities are entirely eliminated. Hubs act as purification gates, ensuring that the shared pipeline asset only handles standardized, utility-grade CO_2 from hub gates.

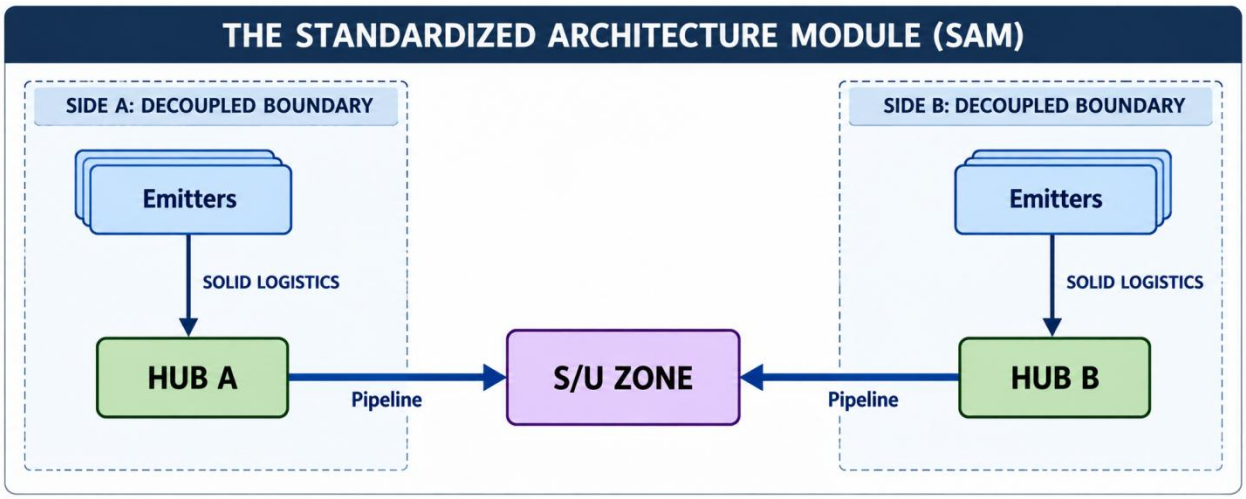


Figure 2: Blueprint of the Standardized Architecture Module (SAM / HOPT-AS Benchmark).

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5. Comprehensive Investor Risk Decoupling Matrix

The table below tracks how specific project finance, regulatory, operational, and counterparty risks are progressively neutralized or systematically dropped at each subsequent stage of the architectural evolution.

Case / Architecture	Stranded Asset Risk (Buried Capital Loss)	Capital Intensity Risk (CapEx Sunk)	Cross-Chain Default Risk (Offtake Link)	Single Point of Failure (SPOF) Risk	Phase / Purity Liability (Cross-Contamination)
Case 0 (Isolated Trunk)	**Absolute (100%).** No functional pathways. Asset is dead capital from day one.	**Absolute.** 100% upfront capital exposure with zero revenue potential.	**Absolute.** No counterparties exist; asset is immediately dead.	**Critical.** Asset has zero network utility.	**None.** No gas is moving through the system.
Case 1 (Binary Link)	**Extremely High.** Default of either the single source or sink permanently strands 100% of the pipe.	**Extremely High.** Capital locked into a rigid link before a single tonne moves.	**Critical.** Any plant shutdown kills 100% of cash flows.	**Critical.** Any localized leak or permit suspension collapses the business model.	**High.** Total exposure to a single emitter's gas impurities corroding the line.
Case 2 (Source Aggregation)	**High.** Downstream destination well failure or legal freeze strands the entire upstream trunkline.	**High.** Heavy trunk pipeline capital remains concentrated and exposed.	**Medium-High.** Destination well failure still paralyzes upstream value.	**Critical.** Main trunkline represents an unmitigated physical and financial SPOF.	**Severe.** Multiple emitters blend raw gas, making it difficult to contractually isolate purity liability.
Case 3 (Solids + Trunk)	**Medium-High.** Source-side steel exposure is gone, but main trunk	**Medium-High.** Feeder pipe CapEx eliminated, but main trunk line	**Medium.** Upstream defaults mitigated via flexible delivery; downstream risk	**Critical.** Central trunkline remains a single physical and revenue	**Medium.** Source hubs act as purification gates, protecting the main trunk line from raw

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	remains fully exposed to downstream stranding.	CapEx remains high.	remains binary.	bottleneck.	emitter impurities.
Case (i) (Pipeline Mesh Grid)	**Low.** Inter-hub bridge cannot be easily stranded due to dynamic bi-directional flow support.	**Medium.** Infrastructure capital is distributed modularly between hubs over time.	**Low.** If Hub A defaults, Hub B dynamically reverses flow, saving the central S/U cash flows.	**Slashed (Twin Engine).** Bi-directional grid isolates leaks without halting regional operations.	**Medium-High.** Rigid pipeline feeders from emitters still pass raw purity risks directly into local hubs.
Case (ii) / HOPT-AS Benchmark	**Theoretical Minimum.** Multi-hub asset bridge is immune to localized source or sink failure.	**Theoretical Minimum.** Pipeline asset exposure limited to a short, high-value inter-hub bridge.	**Theoretical Minimum.** Complete offtake flexibility; emitters can be swapped out overnight.	**Theoretical Minimum.** Network contains no rigid perimeter lines or single delivery straws.	**Theoretical Minimum.** Grid only handles standardized, utility-grade CO_2 from hub gates.

6. HOPT-AS as the Universal Master Grid

A primary conclusion of this framework is that **the HOPT-AS framework [Case ii] is the Universal Master Grid.** Every other configuration explored in infrastructure planning is a mathematically and topologically restricted subset of this master module.

Because any regional infrastructure network can be dynamically decomposed back into independent segments of **Case 0**, the entire architectural evolution can be modeled as a systematic layout reduction from the master grid down to its singular components:

- **The Pipeline Mesh Constraint [Transition to Case i]:** Replace the flexible solid boundaries of HOPT-AS with permanent steel feeder pipelines for all emitters.

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- **The Network Severance Constraint [Transition to Case 3]:** Sever the alternative inter-hub routing pathways and completely isolate a single hub to feed a dead-end delivery straw.
- **The Upstream Rigidization Constraint [Transition to Case 2]:** Convert the flexible vehicular solid logistics of Case 3 back into fixed, heavy-gauge feeder pipelines at the emitter boundary.
- **The Node Elimination Constraint [Transition to Case 1]:** Strip away the aggregated multi-emitter and multi-sink nodes of Case 2 until only a single source and a single destination remain.
- **The Decoupling Failure Constraint [Transition to Case 0]:** Disconnect the final industrial counterparty nodes entirely from the asset, leaving only a bare, non-functional pipeline segment.

This architectural mapping alters how project developers approach routing and deployment. A developer forced by initial budget constraints to build a high-risk, single binary link (Case 1) today does not have to engineer a legacy dead-end asset. By utilizing the HOPT-AS benchmark as the ultimate blueprint, engineers can optimize the initial pipeline's diameter, metallurgical thresholds, and corridor alignment from day one. This guarantees that the early-stage asset can natively serve as an integrated component within a resilient, multi-hub HOPT-AS mesh grid tomorrow.

7. Conclusion

By removing the heavy trunk pipeline and placing utilization sites in the middle of an interconnected hub loop, the foundational nature of CCUS investing changes. It shifts from high-risk, volatile project finance to a stable, utility-style asset grid. The **Hub-Only Pipeline Topology Architecture Standard (HOPT-AS)** establishes a universal benchmark that allows private capital, commercial banks, and sovereign infrastructure developers to evaluate, phase, scale, and govern regional carbon management networks safely, predictably, and with bankable confidence.

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Annex A: The Mixed/Hybrid Module Variant

In real-world deployment, large anchor emitters—such as mega-scale steel mills or cement plants—produce volumes that exceed the practical capacities of rail or truck logistics. To integrate these assets without derailing the core framework, we introduce the **Mixed Module** as an informative variant.

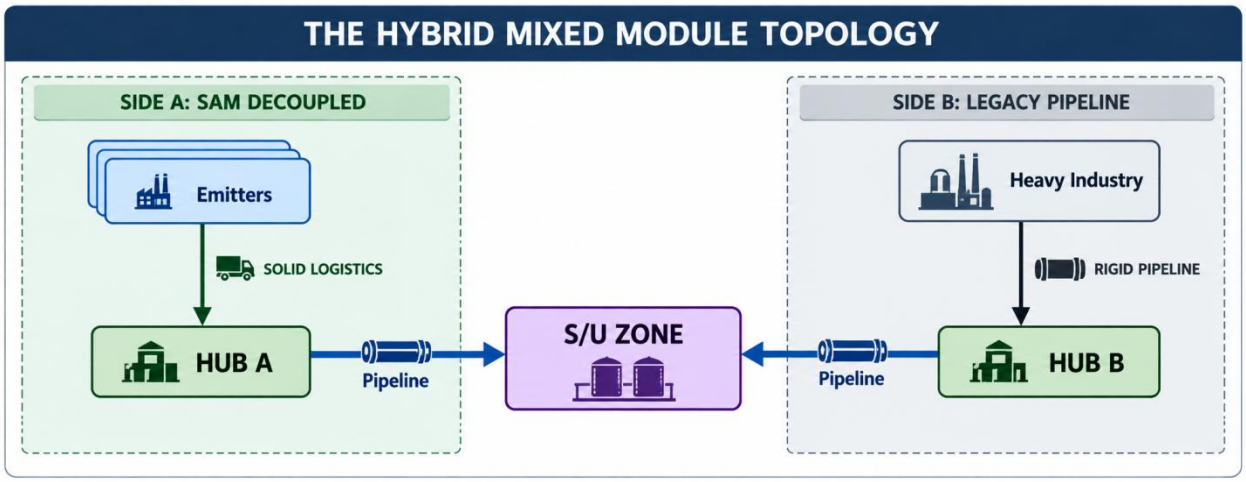


Figure 3: Topology of the Hybrid CCUS Mixed Module.

Mechanics of the Mixed Case:

- **Side A (The SAM Standard):** Emitters utilize solid logistics to reach Hub A, preserving maximum modular elasticity.
- **Side B (The Legacy Corridor):** Heavy industrial plants connect directly to Hub B using fixed pipelines to accommodate high continuous volumes.
- **Risk Containment:** While Side B reintroduces localized asset underutilization risk, the systemic risk is structurally contained. Because Hub B is linked across the balancing bridge to Hub A, any supply collapse on the pipeline side can be immediately counterbalanced by increasing vehicular solid delivery to Hub A, maintaining stable pressure and protecting the central S/U zone from capital stranding.

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Stepwise Evolution of CCUS Pipeline Architecture

From Case 0 to Case (ii) – The Hub-Only Pipeline Topology Architecture Standard (HOPT-AS)

Case 0 — The Isolated Trunkline (Absolute Capital Loss)



Pipeline segment
(no emitters, no S/U endpoints)

Risks at this level

- 100% stranded asset
- DSCR = 0
- Capital trapped in non-functional buried steel
- Zero utility financial anchor

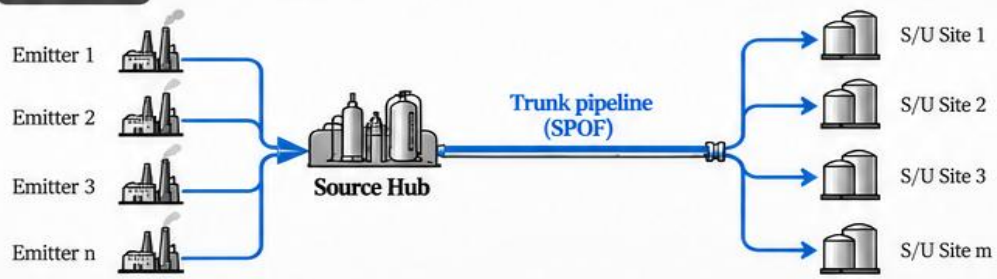
Case 1 — Simple Binary Link (The Cross-Chain Trap)



Risks at this level

- Extreme stranded asset risk
- No structural optionality
- Downtime, bankruptcy, or permit withdrawal at either end drops revenue to zero

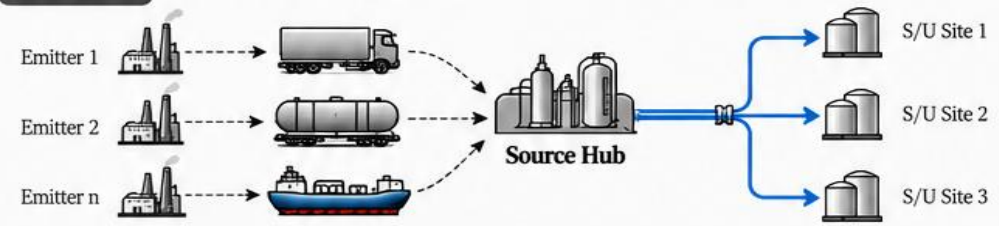
Case 2 — Source Aggregation (The Backbone Bottleneck)



Risks at this level

- High stranded asset risk
- Upstream volumetric risk partially mitigated via multi-source aggregation
- Centralized trunk pipeline is a physical and financial Single Point of Failure (SPOF)
- A single pipeline fracture, pressure anomaly, or localized injunction halts 100% of regional cash flow

Case 3 — Upstream Decoupling (The Logistical Buffer)



Risks at this level

- Medium-High stranded asset risk
- Upstream asset stranding risk reduced (factory-side investments removed)
- Emitters can alter capacity or exit without leaving stranded assets
- Downstream trunkline still fully exposed to stranding if destination cluster fails

Case (i) — Post-Mirror (Balanced Inter-Hub Mesh)

(Mirror image of Case 2 – Trunkline eliminated)

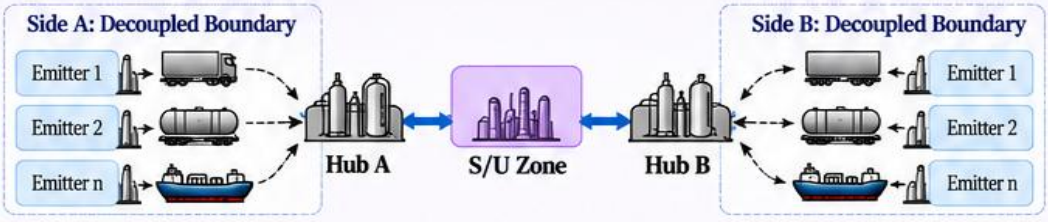


Risks at this level

- Downstream SPOF eliminated
- Inter-hub pipeline still carries risk of localized failure
- Upstream emitters are still pipeline-connected (factory-side investments remain)

Case (ii) — The Hub-Only Pipeline Topology Architecture Standard (HOPT-AS)

(Mirror image of Case 3 – Standardized Architecture Module, SAM)



Risks at this level (Least Risk)

- No trunkline, no single SPOF
- Minimal stranded asset risk
- Residual risks: localized hub failure, regional demand shocks, or S/U zone under-utilization (mitigated by modular design and multiple S/U sites)

Higher Risk

Lower Risk

Legend: = CO_2 emitter (industry) · = Hub (compression, dehydration, etc.) · = S/U site or S/U zone (storage or utilization) · = Pipeline (CO_2 flow) · = Logistics (rail / truck / barge) · = Truck · = Rail · = Barge/Ship