



Designing CO₂ Transport Infrastructure for CCS Scale-Up: Scenario-Based Planning from Denmark to Europe

Introduction

Carbon capture and storage (CCS) is increasingly recognised as an important component of European industrial decarbonisation, particularly for sectors with process emissions or limited access to alternative mitigation options. However, the deployment of CCS depends on more than capture technology. It requires a functioning value chain connecting emitters, transport infrastructure, storage sites, monitoring systems and long-term liability arrangements.

CO₂ transport infrastructure represents a particular challenge. It is capital-intensive, long-lived and often subject to significant demand uncertainty during the early stages of market development. The first users may not be able to carry the full cost and risk of infrastructure intended to serve a much larger future market. At the same time, infrastructure designed around a small number of early projects may constrain later expansion and reduce interoperability with neighbouring networks. The planning challenge is therefore to preserve optionality without creating unjustified over-dimensioning.

These challenges are amplified in Europe, where sources and storage sites are distributed across different countries, regulatory jurisdictions and industrial regions. Cross-border transport, differing CO₂ specifications, permitting processes, third-party access, liability arrangements and the interaction with the EU Emissions Trading System all influence the feasibility and bankability of regional CCS systems.

This contribution develops a practitioner-led system-design perspective on how CO₂ transport infrastructure can enable CCS deployment rather than being developed only as a series of project-specific connections. It draws on lessons from the Danish CCS tender, publicly available European policy documents, existing research and emerging regional infrastructure initiatives. The objective is not to propose one preferred ownership model or transport technology, but to identify conditions that allow different infrastructure models to develop and interact over time.

Method and/or Theory

This contribution is a conceptual and practice-based paper rather than a new techno-economic modelling exercise. It synthesises existing evidence through a structured framework covering four dimensions: demand aggregation and credible anchor volumes; infrastructure architecture and the relationship between shared backbones and project-specific connections; phased deployment and the balance between robust backbone capacity and early utilisation; and risk allocation, governance and interoperability across national borders.

The framework distinguishes between theoretical CO₂ potential, technically feasible flows, probable deployment and volumes realistically available within a defined time horizon. This distinction is important because infrastructure planning based on maximum theoretical capture volumes may result in over-dimensioned assets or stranded capacity. Conversely, planning only around fully committed projects may prevent future users from connecting and reinforce fragmented systems.

Transport infrastructure is considered as a combination of pipelines, shipping, receiving terminals, intermediate hubs and, where relevant, other logistics solutions. The analysis therefore does not assume that a European CCS system must consist of one continuous pipeline network. Instead, it considers whether different regional systems can interact through common technical, regulatory and commercial interfaces.

The Danish CCS tender is used as a relevant policy case because capture projects, transport and storage were expected to develop within a common competitive framework despite having different risk profiles and development timelines. Recent scenario-based techno-economic work on German CO₂ pipeline infrastructure is used as a reference for examining robust backbone design, local sinks, transit flows and the limitations of static full-build planning. European infrastructure initiatives and policy developments are used to discuss how early assets can support wider network development over time.

System-design considerations



Transport infrastructure is a system asset. Shared CO₂ transport cannot be treated solely as a service purchased by individual emitters. It has characteristics associated with strategic infrastructure: high upfront costs, long asset lives, network effects and significant benefits from future connectivity. This does not imply that all transport infrastructure should be publicly owned or that an extensive national network should be built in advance. It does suggest that early infrastructure decisions should be assessed against their ability to support future users, additional storage options and cross-border connections.

A project-by-project approach may produce efficient short-term solutions for individual users while failing to deliver the infrastructure configuration most valuable for the wider system. This creates a risk of path dependency, where early technical specifications, capacity decisions or contractual arrangements make later integration more difficult or expensive. The relevant question is therefore not whether projects should proceed, but whether early projects can become anchors for an expandable and interoperable system.

Infrastructure planning should be based on a portfolio of credible and time-specific CO₂ flows rather than on either maximum theoretical potential or a narrow list of fully committed projects. Relevant criteria include facility-level emissions and capture profiles, expected timing of investment decisions, geographical concentration, CO₂ quality and conditioning requirements, access to storage and alternative transport routes, opportunities for future expansion, energy-system integration, and regulatory and commercial maturity. Scenario testing can identify corridors that retain value across several plausible futures.

This approach supports regional hubs and corridors where sufficient anchor demand exists, while preserving the option to connect additional emitters as the market develops. It also recognises that different regions may require different infrastructure solutions. A dense metropolitan cluster, a dispersed regional industrial base and a large coastal storage development should not necessarily be subject to the same infrastructure model. Pipelines may provide the long-term backbone, while shipping and other transport modes can support early connections, smaller volumes and storage optionality during ramp-up.

Risk should be allocated to the actor best placed to manage it. Capture projects should retain risks they can influence directly. Infrastructure operators and storage developers should carry risks associated with the performance and availability of their assets. Public authorities may need to address residual system risks where infrastructure has wider public value but cannot initially be financed on a purely commercial basis.

Possible instruments include public co-financing, state-backed lending, regulated asset-base models, contracts for difference, capacity commitments or other forms of targeted risk-sharing. The appropriate instrument will depend on the maturity and characteristics of the specific value chain. The central principle is that support should reduce structural risk and create future market capacity, rather than simply compensate for an isolated project's cost overrun.

A functioning European CO₂ infrastructure system also requires clear minimum conditions for CO₂ composition and quality, measurement, reporting and verification, allocation of responsibility, third-party access, capacity allocation, tariff principles, permitting interfaces and compatibility with EU ETS accounting and cross-border transport rules. Minimum rules need not prescribe every commercial relationship, but they should provide sufficient certainty for interoperable investment. Cross-border transit should be considered in network dimensioning from the outset, since it can improve utilisation and alter the economics of shared corridors.

For Denmark, the strategic question is not simply how much CO₂ can be captured or stored nationally. It is also which functions Danish infrastructure can perform in a wider European system. These may include regional collection hubs, receiving and export terminals, connections to North Sea storage, storage services for foreign emitters or links to larger industrial corridors. A European CCS system does not require one physically continuous network, but it does require compatible technical, regulatory and commercial interfaces.



Conceptual architecture for an expandable CO₂ transport system

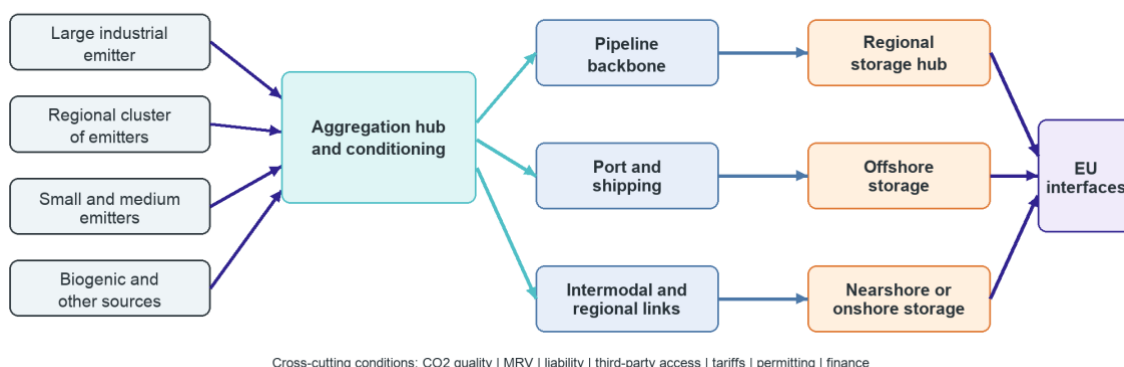


Figure 1. Conceptual architecture for an expandable and interoperable CO₂ transport system.

Conclusions

CO₂ transport infrastructure is one of the central enabling conditions for large-scale CCS deployment. Its development should be guided by the needs of a growing system rather than by the requirements of individual projects alone.

The system-design perspective developed in this paper supports five principles: plan around credible and time-specific CO₂ flows; use early projects as anchors for expandable infrastructure; develop corridors in stages while preserving optionality; differentiate infrastructure models according to regional and industrial characteristics; and allocate risk to the actors best able to manage it, with targeted public de-risking where wider system benefits justify it. Minimum requirements for interoperability, third-party access, MRV, liability and cross-border transport are necessary enabling conditions.

The transition from project support to system enablement does not mean abandoning individual projects. It means ensuring that projects capable of creating early momentum can also become building blocks of a more open, bankable and European CO₂ transport system. The central implementation challenge is to move from a robust conceptual backbone to a phased build-out that remains financeable at low initial utilisation.

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