Transport Optimization and Impurity Management in Shared CO_2 Transport Networks with Intermediate Storage

Introduction

The expansion of carbon capture, utilization, and storage (CCUS) in Europe requires the development of cost-effective, flexible, and reliable CO_2 transport networks that can integrate multiple emitters and transport modes. Shared hubs, intermediate storage terminals, and multi-source CO_2 clusters introduce complexity due to varying impurity profiles and mixing of CO_2 with different transport conditions. The strict CO_2 purity specifications from Northern Lights[1.], Aramis[2.], and Porthos[3.] reflect the uncertainty related to impurity origins, thermodynamic behavior, and long-term impacts on materials and safety. CCUS chain elements such as liquefaction units, cargo vessels, intermediate storage tanks, and downstream pipelines are affected differently by impurities, increasing the need for robust, system-wide impurity management strategies.

Physical and chemical interactions of impurities including shifts in the vapour–liquid equilibrium (VLE), hydrate formation, acid formation, corrosion, and HSE risks may impact transport efficiency, energy demand, and infrastructure integrity. As more emitters tie into shared infrastructure, cross-contamination and impurity accumulation become realistic risks that must be understood and mitigated. The investigation in the GigaCCS project shows that impurity transfer is most likely to occur in liquid CO_2 chains through gas-phase exchange in equilibrium vent lines during ship loading and unloading. This behavior can result in impurities being unintentionally transferred between emitters, especially over repeated transport cycles.

Methodology and background

This extended abstract synthesis technical insights alongside the methods developed in GigaCCS, which aims to develop a techno-economic decision-support tool for optimal purification strategy selection. The objective is to evaluate where purification should occur along the chain (source, hub, or hybrid), how blending affects impurity limits, and how to design shared infrastructure to minimize cost and risk.

In liquid CO_2 transport chains, the use of equilibrium vent lines during loading and unloading operations is a primary driver of impurity transfer. When liquid CO_2 is pumped into or out of cargo tanks, the vapour-phase CO_2 must be vented between the ship and the intermediate storage to maintain pressure balance, see figure 1. This gas-phase exchange allows volatile or reactive impurities from one emitter to transfer indirectly to others. Over multiple voyages, accumulation can occur in intermediate tanks and reliquefaction units, and in extreme cases impurities may cycle back toward upstream facilities through condensate return streams.

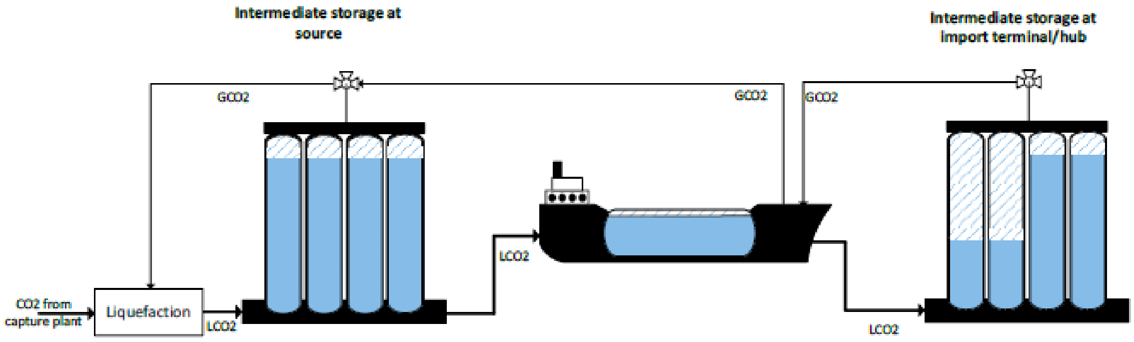

Figure 1: *The interphase between the CO_2 cargo ship and intermediate storage.*

The techno-economic framework developed in GigaCCS follows a structured workflow designed to evaluate purification strategies across the CO_2 value chain. The work begins with a comprehensive system definition, in which impurity limits, emitter characteristics, transport conditions, and hub configurations are established to ensure a consistent analytical basis across scenarios. Building on this foundation, a screening analysis is carried out to compare alternative purification strategies, including purification performed directly at the emission source, centralised purification at the hub, or hybrid solutions that distribute purification steps along the chain. To capture the variability expected in real cluster configurations, the framework then develops three to four representative scenarios that reflect differences in CO_2 compositions, impurity types, transport modes, and chain layouts. These scenarios form the basis for a detailed techno-economic analysis evaluating capital and operational expenditures, energy requirements, operational risks, and key cost drivers associated with each purification option. Finally, the results from these analyses are synthesised into a decision-support tool that enables users to identify the most cost-efficient and operationally robust purification strategies for clusters with multiple CO_2 sources.

Results and Discussion

Impurities present in the CO_2 streams can affect transport and storage performance through physical, chemical, and operational mechanisms. Physically, several components modify vapour–liquid equilibrium, increase compression energy demand, or promote hydrate formation under typical pipeline and reservoir conditions. Chemically, certain components accelerate corrosion, form acids, or degrade metallic and non-metallic materials. From an operational perspective, impurities can lower storage efficiency, push CO_2 quality outside specification, and introduce additional health, safety, and environmental risks. Water and oxygen are among the most critical impurities, as their combined presence can generate corrosive acids such as nitric and sulphuric acid, increasing the likelihood of material degradation. Reactive acid gases, including NO_x, SO_2, and H_2S, further intensify corrosion hazards and bring additional safety concerns due to their toxicity and reactivity. Non-condensable gases such as nitrogen, argon, methane, and hydrogen do not directly corrode materials but reduce system efficiency by lowering CO_2 density and increasing compression requirements. Impurities originating from solvent-based capture processes, including amines and their degradation products, may also contribute to equipment degradation or raise HSE issues.

These effects rarely occur in isolation; rather, impurities often interact, particularly in environments where both water and oxidising agents are present. Such interactions can enhance corrosive potential and make prediction of system behaviour more complex. Due to limited large-scale operational experience and a general lack of detailed impurity composition data from capture plants, current CO_2 specifications tend to remain conservative and reflecting precaution rather than comprehensive empirical understanding

The findings indicate that impurity accumulation in the gas phase of intermediate storage tanks is a realistic operational concern, particularly for volatile species such as NO_x, SO_2, CO, and hydrocarbons, which can migrate into the vapour phase and gradually increase concentrations above specification limits unless vent-gas cleaning or controlled release strategies are applied. At the same time, the evaluation of purification strategies shows that locating purification at the source minimizes the risk of cross-contamination within shared transport systems, but this approach can impose disproportionately high CAPEX burdens on smaller emitters. Hub-based purification benefits from economies of scale and lower per-unit costs, but introduces greater operational complexity and places higher demands on continuous monitoring and impurity tracking, while hybrid configurations offer a compromise by balancing risk reduction with manageable costs. Scenario analyses further demonstrate that impurities such as oxygen, water, and acid-forming species play an outsized role in determining total system cost due to their contribution to corrosion, the need for more robust material selection, and increased purification requirements. The assessment also highlights several knowledge gaps that limit the predictive accuracy of current models, including insufficient data on impurity behaviour over repeated ship loading cycles, incomplete understanding of impurity carry-over from capture plants, limited information on long-term accumulation in intermediate storage, and scarce performance data for liquefaction and purification processes under realistic multi-source operating conditions.

Conclusions

Shared CO_2 transport systems require holistic impurity management strategies across the entire value chain. Liquid CO_2 transport with intermediate storage exhibits realistic impurity transfer risks through gas-phase exchange. A comprehensive techno-economic tool is needed to identify optimal purification location, manage blending effects, and minimize total system cost while maintaining operational safety.

The methodology developed in GigaCCS provides the foundation for such a tool. Future work should focus on improving impurity data, developing robust monitoring strategies, and conducting real-scale operational trials. This will enable the development of scalable CCS clusters aligned with Europe's climate ambitions.

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