



CCS Benchmarking Study

CCS Value Chain Benchmarking Executive Summary



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Executive Summary

This report assesses the costs and configurations of the CCS value chain based on a comparison of over thirty global CCS projects, spanning feasibility through to construction and operation.

The purpose of the report is to provide relevant CO₂ capture, onshore pipeline transport, liquefaction, marine transport and permanent storage project data and information for benchmarking purposes. The assessment is derived from a combination of in-house data from CCS projects executed by io consulting and publicly available data.

The assessment highlights that the costs of CCS can vary widely depending on a range of project-specific factors, such as scale, CO₂ concentration, and storage proximity, as well as macroeconomic trends, including inflation, energy costs, and local labour and material costs. Generally, across the value chain, costs associated with CO₂ capture make up the most significant proportion of the overall cost, followed by transportation and storage.

Figure 1-1: CCS Value Chain Segments

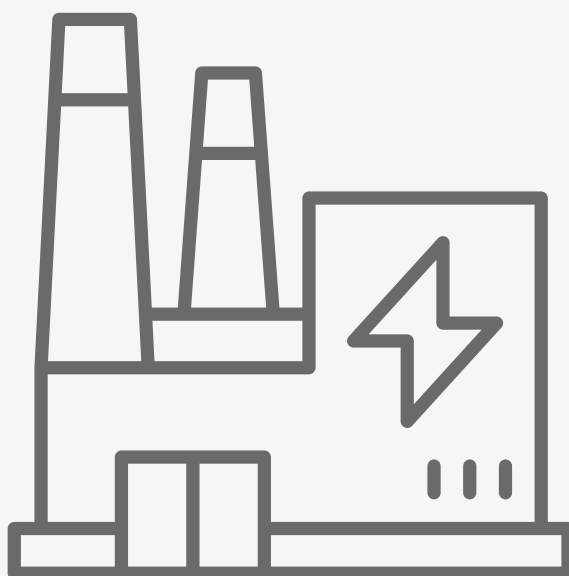


CO₂ capture benchmark assessment

The cost of capture is expected to be between €60 and €120 per tonne of CO₂, depending on the properties of the CO₂ supply stream and the purity requirements of the subsequent transport. Often, these variables are not flexible. Capture technology selection plays a crucial role in optimising capture efficiency while minimising power consumption and other OPEX contributors. There are several technology options for CO₂ capture, with HPC/amine absorption offering high-purity flue gas stream separation, and second-generation oxyfuel or calcium-looping enabling CO₂ separation within existing process stages of hard-to-abate sectors, such as cement production.

The io projects present benchmark costs for seven different capture technologies and demonstrate the tailored decision-making required for capture technology selection, such as Oxykiln II and cryogenic purification in cement capture. Other projects include the Brevik CCS Project in Norway, utilising SLB Capturi amine absorption for a 0.4 mtpa capture capacity, and the \$1 billion Petra Nova project in the US, which captured 1.4 mtpa from a coal plant, representing 90% of design capacity.

CO₂ CAPTURE



€60-€120
PER TONNE CO₂

CO₂ onshore pipeline benchmark assessment

The cost of CO₂ transport via onshore pipeline is expected to be in the range of €60 to €140 per metre-inch for pipeline diameters ranging from 32" to 6" respectively. Pipeline cost is highly sensitive to steel price, with cost increasing from €90 to €112 per metre-inch for a 12" pipeline when steel price increases from \$1/kg to \$2.3/kg. For a 12" 170km pipeline, this steel price variation corresponds to a CAPEX range of €184M to €228M.

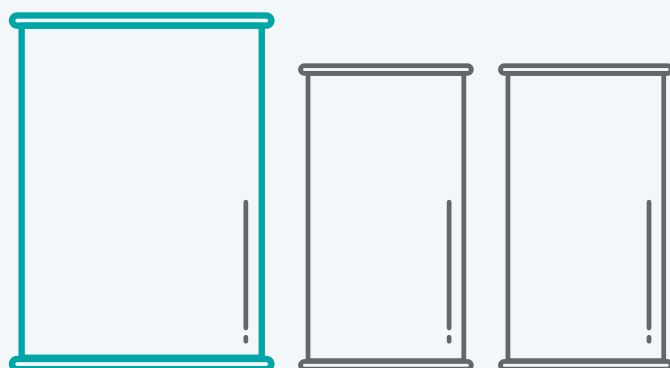
The phase of CO₂ transportation also impacts the cost, routing and safety considerations for pipelines. Dense phase transportation is optimal for long-distance / high-volume applications, minimising CAPEX, but it also raises increased safety concerns due to the high pressure. Gas phase pipelines come at a higher CAPEX but with more manageable rupture characteristics; thus, they are

better suited to populated areas. In either phase, stability is a key design requirement: compression, as identified by flow assurance studies, is critical for maintaining a constant phase throughout a pipeline. Here, too, consideration must be given to CO₂ concentration and impurities.

io projects demonstrate hybrid designs that include both gas and dense-phase pipeline operations (to trade off between pipeline size and routing constraints), as well as a design that analyses brownfield pipeline reuse, demonstrating significant CAPEX savings. In the EU, Porthos and Aramis are combining onshore gas phase transport with dense phase offshore pipelines, and the Alberta Carbon Trunkline presents a mature example of high-throughput, long-distance transport (15 million tonnes per annum, 240 kilometres).

ONSHORE CO₂ PIPELINE

€60-140 per metre-inch
for pipeline diameters
ranging from **32"-6"**



12" 170km pipeline:
€184M-228M
CAPEX depending
on steel price

CO₂ liquefaction benchmark assessment

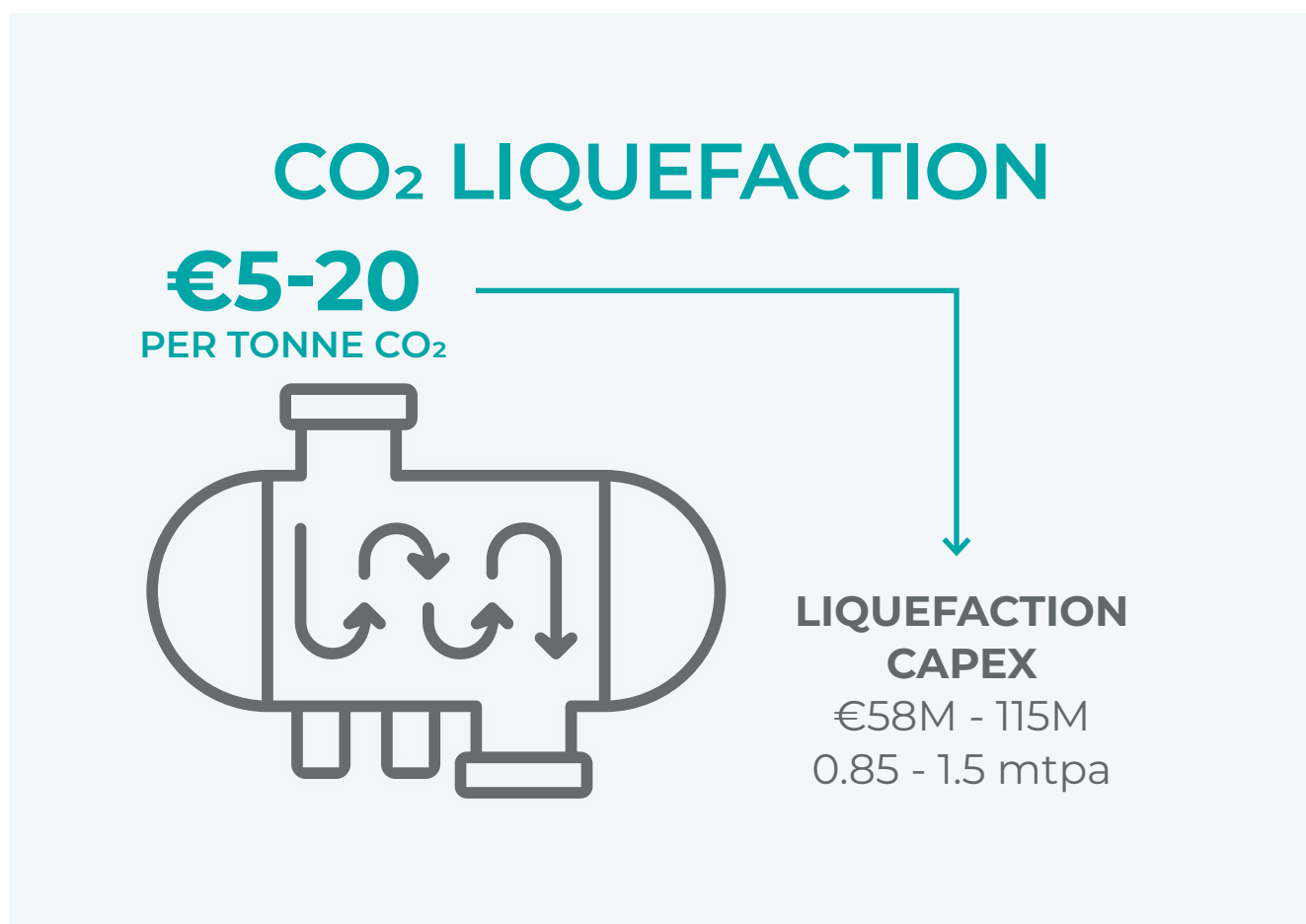
The cost of CO₂ liquefaction can vary from €5 to €20 per tonne of CO₂, depending on technology selection, cooling medium availability, CO₂ composition and system throughput.

Among the available technologies, ammonia or propane-based cascade and hybrid refrigeration systems offer the most cost-effective and thermodynamically efficient solutions for large-scale applications. The ability to co-locate liquefaction infrastructure with low-cost electricity and cold cooling water sources further improves the system's OPEX.

Key liquefaction technology providers include Line Engineering, Air Liquide, Baker Hughes, Technoproject, Pietro Fiorentini, Bright Renewables and Ecospray.

io projects have integrated liquefaction and purification requirements in cryogenic systems for rail or ship transport with CAPEX ranging from €58M to €115M for capacity ranges of 0.85 to 1.5 mtpa.

The Stockholm Exergi 0.8 mtpa BECCS Project utilises Air Liquide Cryocap technology prior to shipping, funded via the national government, the EU (€260M loan from the EIB), and the voluntary CO₂ offtake market. The Olympus Project in Greece plans to liquify 1 mtpa (also Air Liquide) following an EU Innovation Fund award of ~€125M in 2023.



CO₂ shipping benchmark assessment

The cost of a CO₂ ship is between €13M and €20M per year, depending on pressure (LP at ~5 barg, MP at ~15 barg), re-liquefaction systems, and build CAPEX financing. Based on a ship running 52 trips per year with a cargo size of 19,000 m³, the cost ranges are €11-14/tCO₂ for LP vessels and €19-24/tCO₂ for MP vessels. While MP vessels have higher build costs than LP ships, MP offers reduced complexity and power demand, thereby lowering OPEX and onshore liquefaction costs.

The CO₂ ship market is nascent, with only six vessels built or under construction. Operators, engineering companies, and ship builders such as Larvik Shipping/MOL, Mitsubishi Shipbuilding, Exmar, and

Hanwha Ocean are emerging as early movers with dedicated or dual-purpose LCO₂ carrier designs. MP CO₂ vessels, Northern Pioneer and Northern Pathfinder, were built at Dalain Shipbuilding Offshore to be managed by Kawasaki Kisen Kaisha ("K" Line) on behalf of the Northern Lights Joint Venture. Project Greensand in Denmark plans to use CO₂ vessels with a capacity of ~5,500 tonnes, expecting to operate 80–100 voyages annually. CO₂next in the Netherlands combines marine vessels and barges for inland transport, with FEED ongoing.

CO₂ SHIPPING

€13-20M
COST PER SHIP
PER YEAR

CURRENTLY 6 VESSELS
GLOBALY



€19-24
PER TONNE CO₂
FOR MP VESSELS

€11-14
PER TONNE CO₂
FOR LP VESSELS

CO₂ sequestration benchmark assessment

Geological sequestration can cost between €2 and €20 per tonne of CO₂, depending on factors such as well count, offshore or onshore location, availability of legacy wells, or storage site type (saline aquifers or depleted oil & gas formations). DRILLEX cost is typically between €6M and €20M per well.

io projects include consideration of network-based subsea infrastructure for 28 mtpa sequestration in offshore saline aquifers, with DRILLEX costs accounting for nearly half of total CAPEX.

European sequestration continues to develop, with 1.5 mtpa (scaling to 5 mtpa) at Northern Lights, over 10 mtpa at Project Trudvang (scheduled to start in 2029), and 0.4 mtpa (scaling to 8 mtpa) at Project Greensand (planned for 2026).





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