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Life cycle assessment as a tool for evaluating CCS Projects: methodology and regional scenarios

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Life Cycle Assessment (LCA) provides a systematic framework for evaluating Carbon Capture and Storage/Utilisation and Storage (CCS/CCUS) projects beyond the amount of CO_2 captured or injected and economics of it. The study presents an LCA methodology developed within the CTS project for comparison of alternative regional CO_2 transport and offshore geological storage configurations. The approach follows ISO 14040/14044, applies an attributional scenario-based assessment and uses 1 tonne of CO_2 permanently stored as the common functional unit. Four regional cases – Baltic Sea, Black Sea–Romania, Black Sea–Ukraine and Atlantic Coast–Portugal were evaluated in the project. This paper focuses on preliminary LCA of the Ukranian segment of the Black Sea Scenario. Preliminary screening results demonstrate that environmental performance depends on regional system architecture rather than transport technology alone. For the Ukrainian case, DSI reduces screening GHG intensity from 317.8 to 305.7 kg CO_2e/t CO_2 stored and increases net-abatement efficiency from 94.5% to 96.0%, while eliminating the modelled offshore pipeline and fixed marine footprint. In other regions, different trade-offs between operational emissions, material demand and infrastructure footprint are observed. The methodology is additionally extended to consider infrastructure reuse, vessel repurposing and material circularity, providing a broader basis for project-development and investment decisions.

Keywords: life cycle assessment, CCS, CO_2 transport, geological storage, Direct Ship Injection

Introduction

CCS is a one of essential elements of industrial decarbonisation strategies, particularly for sectors in which complete elimination of process related CO_2 emissions is technically difficult. The environmental effectiveness of CCS cannot be assessed solely through the quantity of CO_2 captured or injected. Capture, conditioning, transport, infrastructure construction, injection and long-term storage themselves require energy, materials and infrastructure and therefore generate additional environmental burdens (*Dudu et al., 2025; NORCE Research, 2024)*. Techno-economic analysis alone do not answer this question either.

Life Cycle Assessment LCA provides a suitable methodological framework for identifying these burdens and relating them to the climate-mitigation function delivered by a CCS system. Within the CTS project (CO_2 Transport and Storage directly from a ship: flexible and cost-effective solutions for European offshore storage), LCA is applied according to the general structure of ISO 14040 and ISO 14044: goal and scope definition, Life Cycle Inventory analysis, Life Cycle Impact Assessment and interpretation. The phases are treated iteratively, allowing assumptions, boundaries and inventories to be refined when additional project-specific information becomes available (*International Organization for Standardization, 2006; Kurylo et al., 2026*).

An important methodological principle is that LCA is not used to establish a universal environmental ranking of individual transport technologies. Instead, alternative technical configurations are compared within the same regional CCS system, where CO_2 sources, transport distances, port infrastructure, storage sites and injection conditions are comparable.

Objective and Methodological Approach

The objective of the study is to establish a transparent and reproducible framework for evaluating the environmental and resource performance of technically feasible CCS configurations and to demonstrate its application to regional CTS scenarios.

The assessment follows the four ISO 14040/14044 stages: goal and scope definition, Life Cycle Inventory, Life Cycle Impact Assessment and interpretation. It is primarily an attributional, scenario-based LCA, using project specific technical parameters from the CTS techno-economic

scenarios. The system boundary follows a cradle-to-grave approach covering capture and conditioning, collection and handling, transport, injection and geological storage, infrastructure construction, operation, maintenance and, where data are available, decommissioning.

The common functional unit is 1 tonne of CO_2 permanently stored in the designated geological storage formation. Two calculation levels are distinguished: the full CCS chain and the transport/injection/storage subsystem. This distinction is important because capture may dominate total energy consumption and GHG (Greenhouse Gas) emissions while remaining identical between alternative transport configurations. Core indicators include GHG intensity, energy intensity, pipeline steel intensity, land occupation, marine infrastructure footprint, net-abatement efficiency and a supplementary infrastructure-intensity score.

The principal indicators selected for the comparative assessment are:

- GHG intensity, kg CO_2e/t CO_2 stored. This indicator expresses the greenhouse-gas emissions generated throughout the assessed CCS chain per tonne of CO_2 permanently stored.
- Energy intensity, MJ/t CO_2 stored. The indicator captures energy used for capture, conditioning, compression, pumping, liquefaction, ship operation, reconditioning and injection.
- Steel intensity, kg steel/t CO_2 stored. Steel demand is used as a practical indicator of material and infrastructure intensity, particularly for pipeline networks, ships and offshore facilities.
- Land occupation, $m^2 \cdot year$/t CO_2 stored. This indicator characterises the terrestrial footprint associated with pipelines, compressor stations, ports, intermediate hubs and other fixed infrastructure.
- Marine infrastructure footprint, $m^2 \cdot year$/t CO_2 stored. The indicator reflects offshore pipelines, receiving platforms and other fixed marine infrastructure.
- Net-abatement efficiency, %. It shows what proportion of the theoretical climate benefit remains after accounting for additional emissions associated with operation of the CCS chain.

A supplementary infrastructure-intensity indicator is also used to represent physical differences that may not be fully captured through GHG or energy metrics alone. It is treated as a project-specific screening metric rather than as a standard ISO LCIA category.

Regional Scenarios and Preliminary LCA Results for the Ukranian one

The CTS assessment covers four regional systems and nine technical scenarios: SHIP (Conventional ship transport scenario) -DSI (Direct Ship Injection) for the Baltic Sea; PIPE (Pipeline transport scenario) -SHIP-DSI for Black Sea-Romania; SHIP-DSI for Black Sea-Ukraine; and PIPE-DSI/hybrid for Atlantic Coast-Portugal. The scenarios are compared within each region, rather than ranked across regions, because their CO_2 sources, transport distances, collection systems, ports and storage infrastructure differ substantially (*Dudu et al., 2025; NORCE Research, 2024)*.

Preliminary screening calculations demonstrate that no single transport configuration provides the same environmental advantage under all regional conditions.

For the Black Sea-Ukraine case, the most pronounced effect results from changing the offshore storage architecture. SHIP and DSI have the same calculated energy intensity of 3,486 MJ/t CO_2 stored, but DSI reduces downstream GHG emissions from 45.4 to 33.3 kg CO_2e/t stored and total screening GHG intensity from 317.8 to 305.7 kg CO_2e/t stored. Net-abatement efficiency consequently increases from 94.5% to 96.0%. The physical infrastructure difference is even more significant. The conventional SHIP configuration includes approximately 55 km of offshore pipeline and about 6,389 t of estimated pipeline steel, whereas these components are absent from the assessed DSI configuration. The corresponding infrastructure score decreases from 47.5 to 19.2. The calculated marine footprint decreases from 0.131 to 0.000 $m^2 \cdot year$/t CO_2, while modelled land occupation remains unchanged at 0.009 $m^2 \cdot year$/t CO_2. In both Ukrainian configurations, the screening model assigns 230 kg CO_2e/t to capture and 39.6 kg CO_2e/t to compression; the principal difference appears in transport and injection emissions: 45.4 kg CO_2e/t for SHIP versus 33.3 kg

CO_2e/t for DSI. Thus, presenting only full-chain totals can conceal the actual environmental effect of downstream configuration changes.

These results confirm that LCA should identify environmental trade-offs, rather than seek a universal ranking of PIPE, SHIP or DSI.

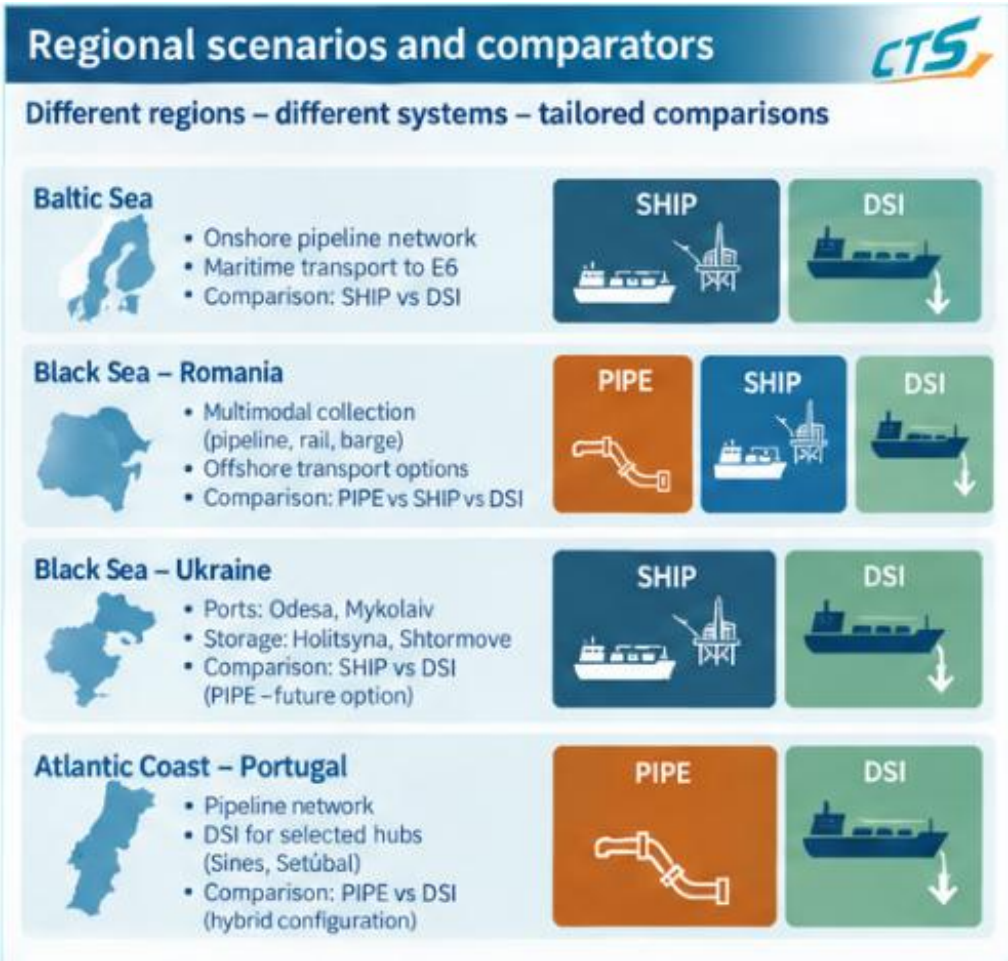

Рис. 1. Regional CCS scenarios and comparative transport and storage configurations in the CTS project.

Extended System Boundary and Circularity

For project development applications, the core LCA can be supplemented by an extended system boundary: 1)previous asset life; 2) CCS project life; 3) second life / reuse / recycling. This extension is particularly relevant where depleted hydrocarbon fields, existing wells, offshore platforms, pipelines, ports or vessels can be reused or repurposed. The assessment should distinguish new infrastructure from assets that can be directly reused, refurbished or replaced and can quantify the avoided construction, material and environmental burdens associated with reuse.

A second important pathway concerns conversion of existing vessels into CO_2 transport or DSI ships. From the life-cycle perspective, retrofitting can reduce the embodied infrastructure burden because part of the vessel structure and materials already exists, although the environmental benefit depends on remaining useful life and the scale of required modification.

The extended assessment may additionally consider reuse, refurbishment and recycling of steel, alloys, electrical equipment, pumps, compressors, pressure vessels, subsea equipment and structural modules. These circularity elements are recommended as supplementary scenarios, rather than part of the default core LCA, to preserve comparability of the principal regional results.

Discussion

The preliminary results demonstrate that the environmental performance of CCS is determined by the interaction of operational emissions, energy consumption and infrastructure

configuration. A configuration with lower operational emissions may require more pipelines, steel or fixed offshore infrastructure, while an alternative with somewhat greater operational energy demand may reduce permanent infrastructure and associated land or marine footprint.

This is particularly important at early project stages, when decisions regarding PIPE, SHIP, DSI, infrastructure reuse and phased development are still flexible. LCA can therefore be integrated with techno-economic assessment not only as an environmental reporting procedure, but as a tool for scenario selection, infrastructure optimisation and project development.

Conclusions

Life Cycle Assessment provides a structured basis for evaluating CCS systems beyond the nominal quantity of CO_2 stored. The use of a common functional unit and two calculation levels makes it possible to reveal environmental effects that may otherwise be masked by the dominant capture stage.

Preliminary CTS results confirm that regional architecture is decisive. In the Ukrainian case, DSI reduces GHG intensity, pipeline steel requirements, infrastructure intensity and marine footprint relative to the conventional SHIP configuration. The Romanian and Portuguese cases demonstrate different trade-offs, confirming that conclusions cannot be transferred automatically between regions.

Extending the conventional LCA boundary to include reuse of depleted fields, repurposing of vessels and infrastructure, and circular recovery of materials further strengthens the methodology for long-term CCS project planning.

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