Making oCCS a Reality

From Regulatory Framework and System Application to Value Chain Uptake

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The strategic case

oCCS adds a practical third lever for ships that will continue using carbon-based fuels.

It complements efficiency and future fuel switching by capturing CO_2 before it reaches the atmosphere.

1 Efficiency

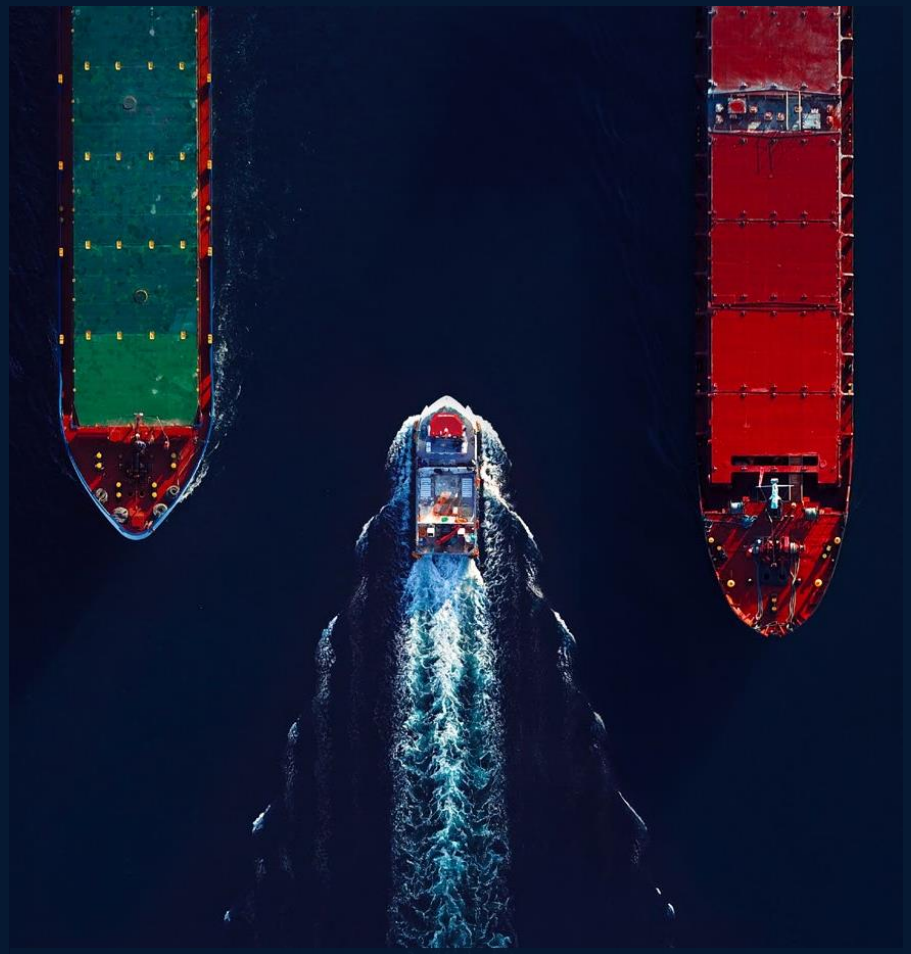
Reduce the energy a ship needs.

2 Cleaner fuels

Lower the carbon content of energy.

3 oCCS

Capture the remaining exhaust CO_2.



Best-fit candidates combine long remaining life, priced-carbon exposure and credible offloading.

Why the decision is moving up the agenda

The external pressure is rising faster than fleet replacement and fuel infrastructure.

Carbon cost is real

EU ETS covers 100% of intra-EEA emissions and 50% of voyages into and out of the EEA. Allowances were around €75–80/t in early 2026.

The fleet is mid-life

Average merchant-fleet age was 13.4 years; 39% of global tonnage was over 15 years old at the start of 2026.

Fuel supply is constrained

Only about 4% of the near-zero-emission fuel plants needed by 2030 had reached final investment decision.

Implication

For ships with meaningful life remaining, efficiency alone may not deliver deep enough cuts and full fuel conversion may not be viable. oCCS offers an additional transition pathway.

oCCS is much more than a capture unit.

oCCS is an end-to-end chain, not a box

Capture

Separate CO_2 before, during or after combustion.

Condition & Store Onboard

Purify, compress, dehydrate and liquefy or stabilise.
Hold safely onboard

Offload

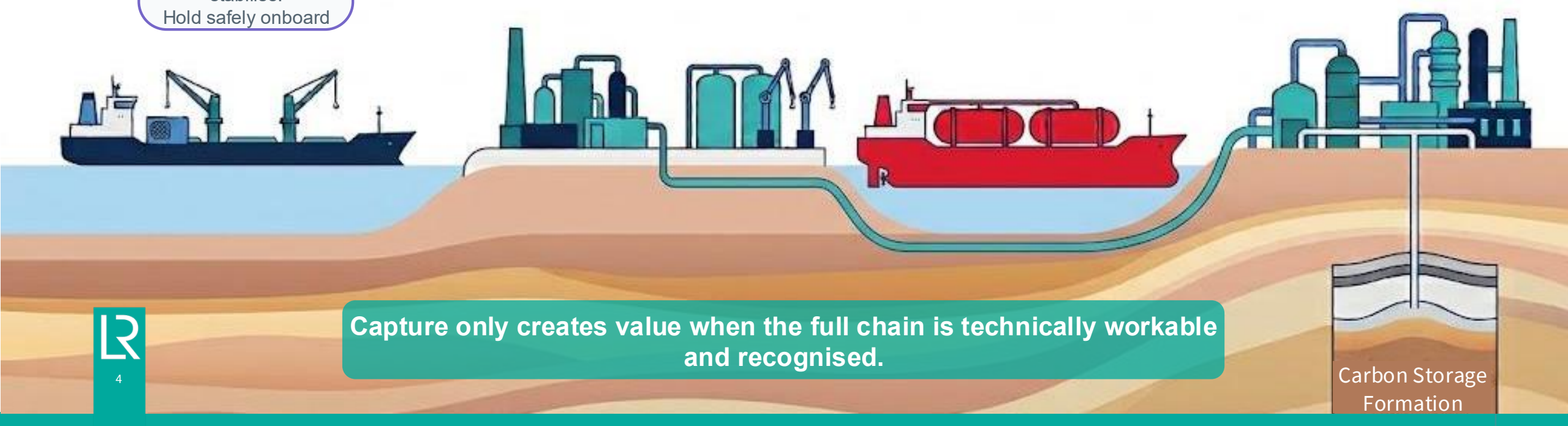
Transfer to shore, ship or container pathway.

Transport

Move through terminal, carrier or pipeline infrastructure.

Store / Use

Reach permanent geological storage or qualifying utilisation.



Capture only creates value when the full chain is technically workable and recognised.

Technology readiness

Type	Technology	TRL	Key Strengths	Key Constraints
Pre-combustion	**Fuel Reforming**	4-5	High capture efficiency through concentrated CO_2 streams	Major changes to fuel and propulsion systems.
	Catalytic Pyrolysis	5	Eliminates gas separation and solvents	High energy demand and solid storage requirements
Post-combustion	**Chemical Absorption**	7-8	Most mature and proven oCCS technology	Significant energy and space requirements
	Membrane Separation	7-8	Compact and modular solution with lower energy demand	CO_2 purity and contaminants sensitivity
	Physical Separation (Adsorption)	3-4	Solvent-free with lower energy demand	Complexity increases with higher capture rates
	Cryogenic Separation	3-4	Produces high-purity liquefied CO_2	High refrigeration energy demand
	Mineralization (Calcium-based)	5-6	Avoids complex gas handling	Increased material-handling demand and volumes for solid storage
	Mineralization (Alkali-based)	5-6	Avoids CO_2 liquefaction and cryogenic handling	High reagent demand and storage
Oxy-Fuel Combustion		2-3	Technology to monitor until marinisation	Very low maturity level

Technology fit by application

The most mature option is not automatically the best option for every ship.

Other routes are use-case plays or next-cycle options.

Route	Potential fit	Advantage	Main constraint
Chemical absorption	Conventional-fuelled deep-sea tonnage	Mature, classable today	Heat duty, chemicals, footprint
Mineralisation	Short-sea and feeder operations	Avoids onboard liquid CO_2	Heavy solids and logistics
Cryogenic separation	LNG carriers and LNG-fuelled ships	Can use available cold energy	High electrical demand
Membrane	Space-constrained applications	Compact and modular	Lower maturity and purity
Pre-combustion	Potential LNG configurations	Concentrated carbon stream	Large process and H_2 systems

What drives the business case

There is no meaningful single cost per tonne for the fleet.

CAPEX

Capture plant, conditioning, storage tanks, structural work and installation.

Energy penalty

Fuel or power demand for regeneration, compression, refrigeration and auxiliaries.

Cargo impact

Lost deadweight, cargo volume, deck area or container slots.

Utilisation

Operating hours and captured tonnes depend on voyage and offloading pattern.

Downstream cost

Reception, transport, permanent storage or qualifying utilisation.

Recognised benefit

Avoided EU ETS cost can be modelled today; other regulatory value remains uncertain.

Where the case is strongest

Four variables matter more than vessel type alone.

10+ years
remaining trading life

High
priced-carbon exposure

Available
credible CO_2 offloading

Tolerable
space, cargo and energy trade-offs

Strong near-term fit

MR and chemical tankers with EEA-anchored trade; LNG-fuelled vessels and LNG carriers; short-sea and feeder operations with frequent EEA calls.

Conditional

Container liner trades; large tankers and bulk carriers where storage and offload patterns align.

Weak today

About five years of remaining life; little carbon-price exposure; no realistic offload access; unacceptable cargo or power penalty.

Regulatory Outlook for oCCS

Current State

- **IMO compliance framework provides no formal credit for captured CO2** under **EEXI, EEDI or CII** frameworks
- **EU ETS** provides a **credible pathway for OCCS recognition**
- **FuelEU Maritime** does **not yet recognize OCCS** performance
- **Cross-border CO2 transport and storage** remain subject to **legal and regulatory uncertainty**
- Lack of clear accounting methodologies leads to **limited investment and scale-up**

Frameworks under development

- **IMO OCCS workplan progressing** with completion targeted around 2028
- **LCA rules under development**
- **FuelEU Maritime review** due in 2027
- **MRV and chain-of-custody** requirements being **defined**
- **Classification societies** providing interim rules and approvals

Key Enabling Factors

Accounting & Compliance
recognition within IMO and EU frameworks

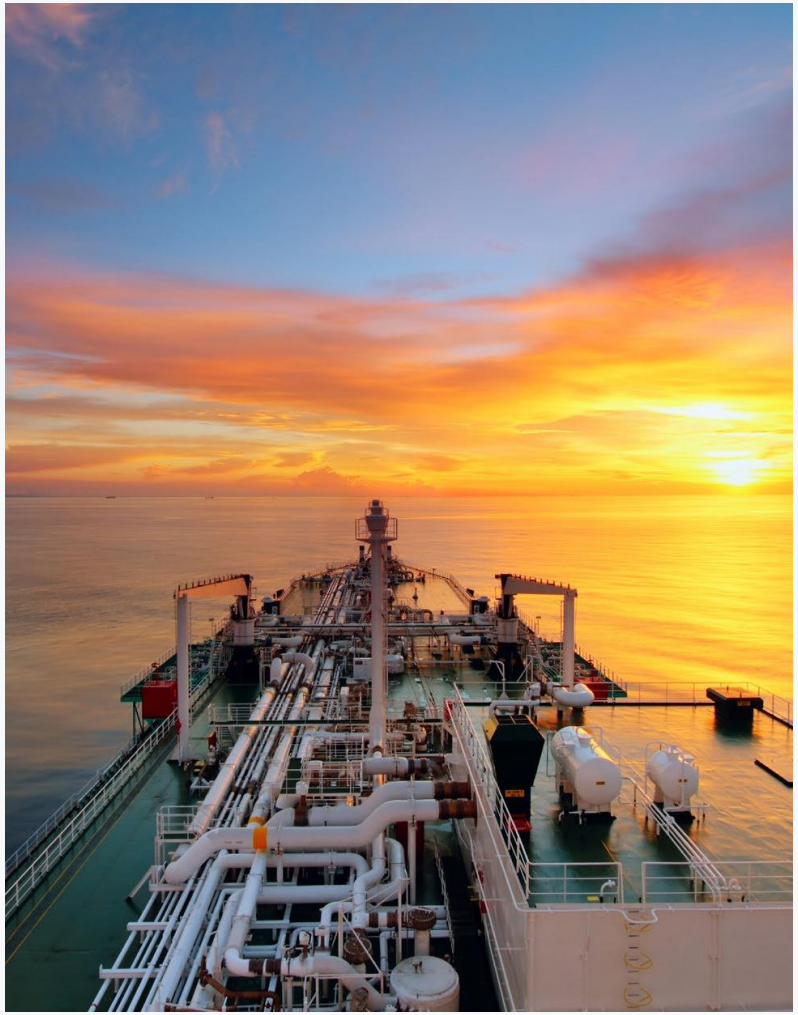
CO2 Infrastructure
reception terminals & transport networks - geopolitical storage capacity & cross-border arrangements

Safety & Standards
harmonized global regulations – class rules & certification – standardized offloading procedures – clear operational guidance

A strong capture rate cannot compensate for insufficient storage, unavailable reception, incompatible CO_2 specifications or missing regulatory credit.

The carbon value chain is the deployment bottleneck

Port reception and chain-of-custody are less mature than capture technology.



Port interface

The current set of ports able to receive ship-captured liquefied CO_2 is small; pressure and purity must match.

Transfer and transport

Fixed jetty, ship-to-ship and ISO container transfer have been demonstrated, but procedures are not standardised.

Storage geography

The most developed chain is concentrated around north-western Europe and the North Sea.

Evidence chain

Captured tonnes require auditable custody from ship through transfer, transport and permanent storage or qualifying use.

Commercial rule: start with the ship's actual ports and storage destination, then size the onboard system.

LCO2 Offloading Concept Study

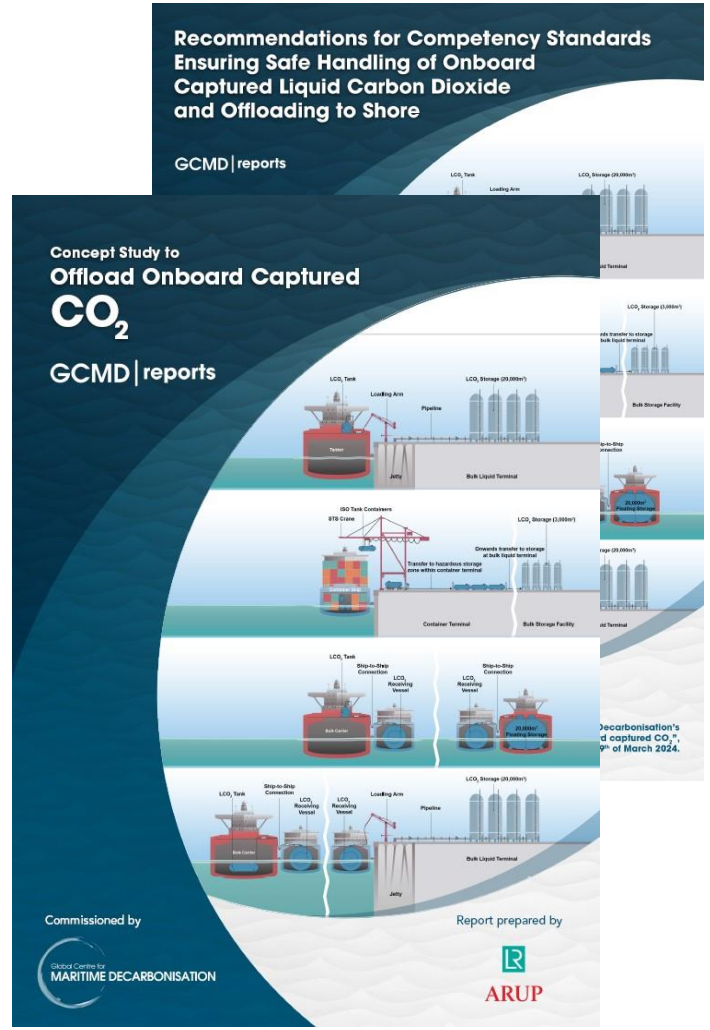
The Global Centre for Maritime Decarbonisation (GCMD) awards its concept study on offloading liquefied CO2 (LCO2) captured onboard ships to Lloyd's Register, supported by their partner Arup.

- Variety of concepts for offloading liquefied CO_2 requiring a consideration of various factors, including vessel types, onboard storage location, transfer modes, intermediate and in-port storage conditions.
  - 13 offloading concepts and their variants were screened, out of which 4 were selected for further analysis.

- Exploring hazards such as when CO_2 is stored at conditions near the triple point where gas, liquid and solid phases of CO_2 co-exist.
  - Sensitive to impurities, and minor changes in temperature and pressure can lead to a phase change from liquid to solid CO_2 leading to hazardous situations, such as blockage in pipes and build-up of pressure.

- Addressing these hazards, a series of safety studies were conducted including a Hazard Identification (HAZID) study, a Simultaneous Operations (SIMOPS) study and a coarse Quantitative Risk Assessment (QRA) study.

- Final report published in April 2024 will highlight recommendations to address these safety concerns that are crucial for parties that are interested in further developing OCCS / LCO_2 offloading concepts.



References

GCMD selects Lloyd's Register for LCO2 offloading concept study (gcformd.org)

GCMD LCO2 offloading safety study (gcformd.org)

Safety must be designed into the system application

oCCS introduces concentrated CO_2, pressure or cryogenic hazards and, for amines, chemical exposure.

CO_2 detection and ventilation

Low-level extraction, oxygen-deficiency monitoring and alarm integration.

Pressure and cold

Relief design, safe discharge locations, compatible materials and triple-point control.

Emergency shutdown

Open exhaust bypass, stop pumps, isolate tanks and maintain ventilation.

Materials and corrosion

Verify metals, coatings, gaskets and elastomers against the actual process stream.

Crew and procedures

Training for solvent handling, tank management, transfer and emergency response.

Risk-based assurance

Use HAZID and HAZOP to carry vessel-specific risks into detailed design.

Four risks shape every application

Each risk must be managed against the vessel’s actual operating model.

1

Regulatory

Uneven recognition, changing IMO rules and cross-border legal constraints.

2

Infrastructure

Scarce reception, incompatible pressure or purity and limited transport capacity.

3

Technical

Energy penalty, routing, safety, sensor performance and storage limitations.

4

Commercial

Carbon-price volatility, CAPEX recovery, cargo loss and offloading cost.

How LR can support the decision

From early feasibility through to in-service performance

Plan approval and AiP

Design-stage assurance against applicable rules and risk assessments before commercial commitment.

ShipRight risk-based certification

A vessel-specific route through design and safety statement, HAZID/HAZOP, final design, construction, commissioning and in-service assessment.

MRV assurance and advisory

Monitoring, verification and chain-of-custody support so captured CO_2 can be recognised under the relevant regime.



A disciplined decision pathway

Move from a vessel-and-trade screen to an assured, auditable operating system.

1 Screen the vessel

Remaining life, route, carbon exposure and space.

2 Name the chain

Ports, CO_2 specification, transfer mode and final destination.

3 Select technology

Capture route, heat/power balance and storage concept.

4 Prove the safety case

AiP, HAZID/HAZOP and risk-based certification.

5 Build the business case

CAPEX, OPEX, cargo impact, penalties and recognised benefits.

6 Verify performance

Commissioning baseline, monitoring and chain-of-custody evidence.

LR Risk Based Certification (RBC)

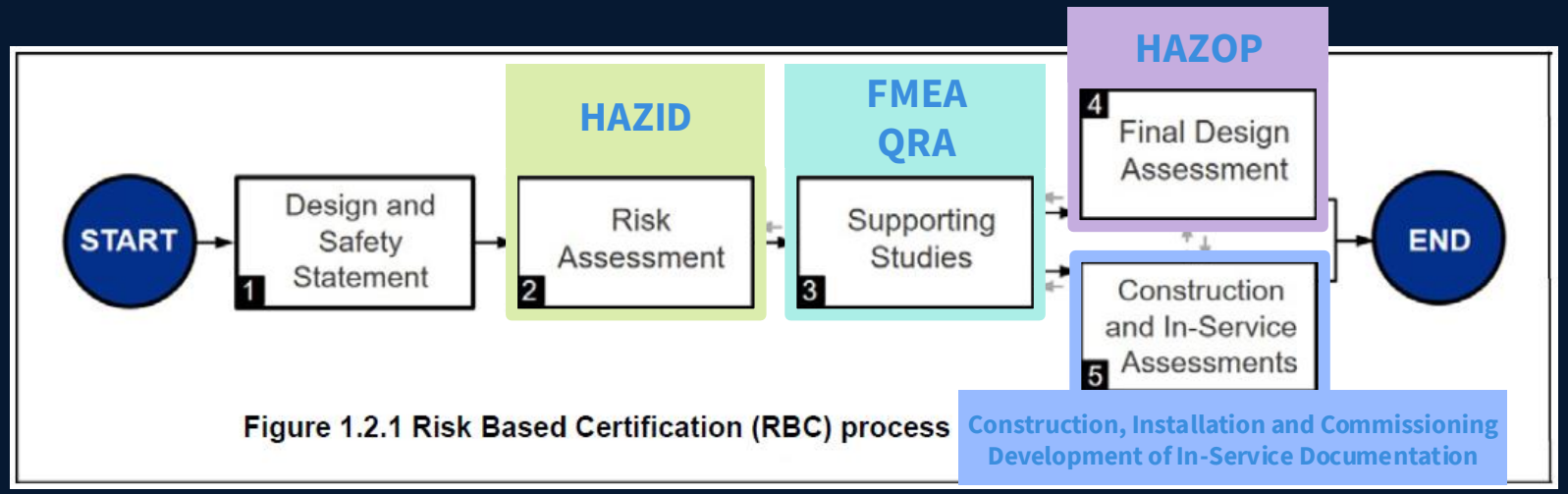


Figure 1.2.1 Risk Based Certification (RBC) process



Onboard Carbon Capture & Storage (oCCS)

Demonstrating technical capability, regulatory compliance and commercial attractiveness

Marine Application

20+
Technology Makers Deep Dive sessions

7+
Onboard Pilot Installations

- GHG reduction potential & regulatory compliance
- Technology Readiness (TRL) & Commercial Readiness Levels (CRL)
- Technical, Engineering, & Design Criteria
- Shipboard pilot feasibility & system installation
- CAPEX & OPEX
- Healthy, Safety, Security & Environmental Criteria
- Commercial & Operation Criteria

Advocacy

17+
Approvals in Principle (AiP) of oCCS systems



Tech Acceleration

9+
Industry Partners

Along with 8 key clients we are working under a specific scope to address challenges relevant to the roll out of Carbon Dioxide shipping.

- WP1: Market Analysis
- WP2: Feasibility Analysis
- WP3: CO2 Shipping – Design aspects
- WP4: CO2 Shipping – Operational aspects
- WP5: Regulatory Framework
- WP6: Training

Carbon Value Chain Focus Group

Indicative Stakeholders

ENERGY EFFICIENCY RETROFIT REPORT

For more information visit lr.org/ccs

Applying Onboard Carbon Capture & Storage to existing ships

| September 2026



Retrofit Research Programme

Thank you

When you partner with LR, you put centuries of collective experience, strong values, and deep maritime and shipbuilding expertise on your side. There is no surer way to build resilience into your overall fleet strategy.

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