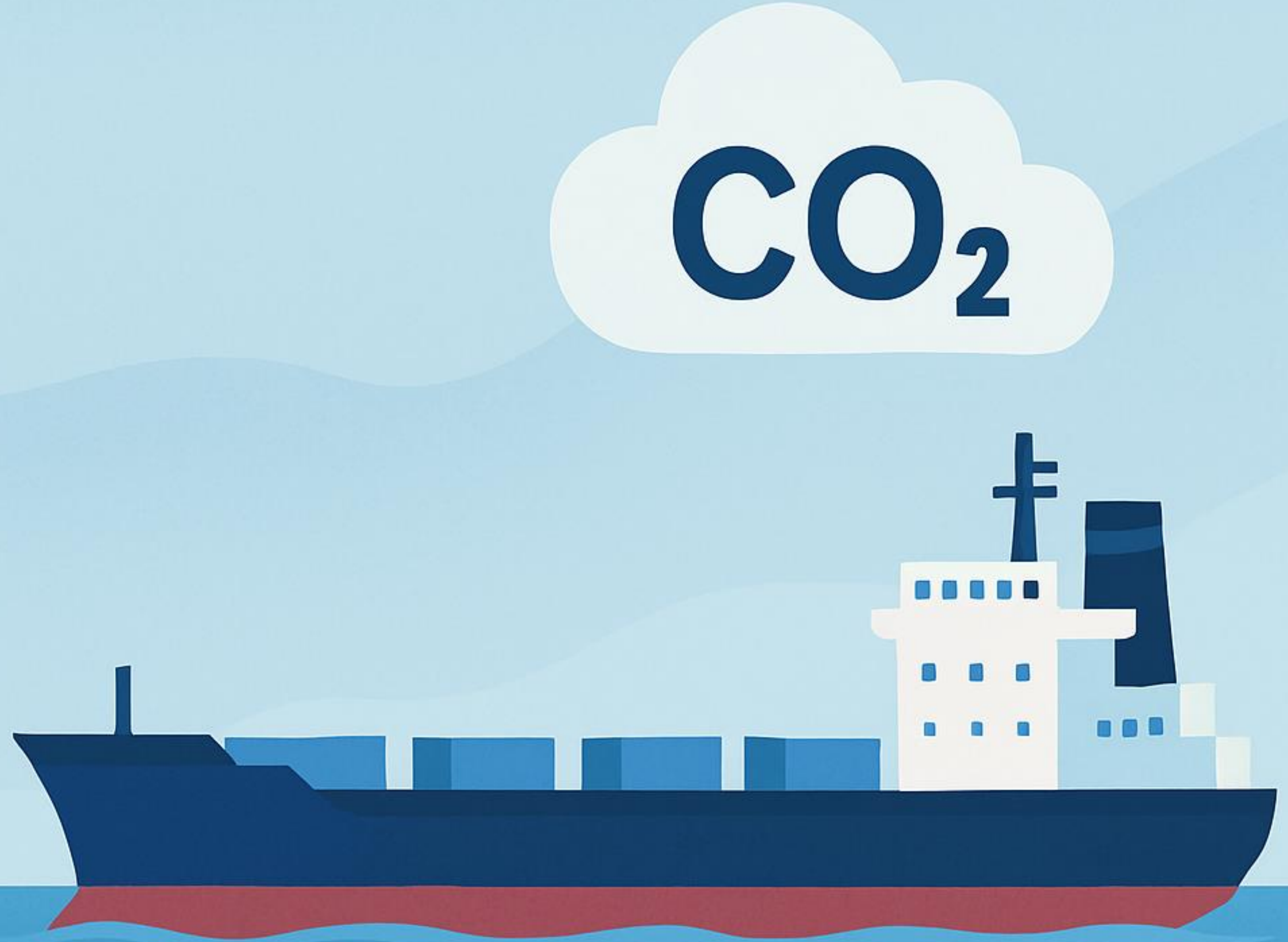
ONSHORE-TO-ONBOARD DECARBONIZATION

TARGETTING EMISSIONS REDUCTIONS IN CONVENTIONAL MARINE SYSTEM



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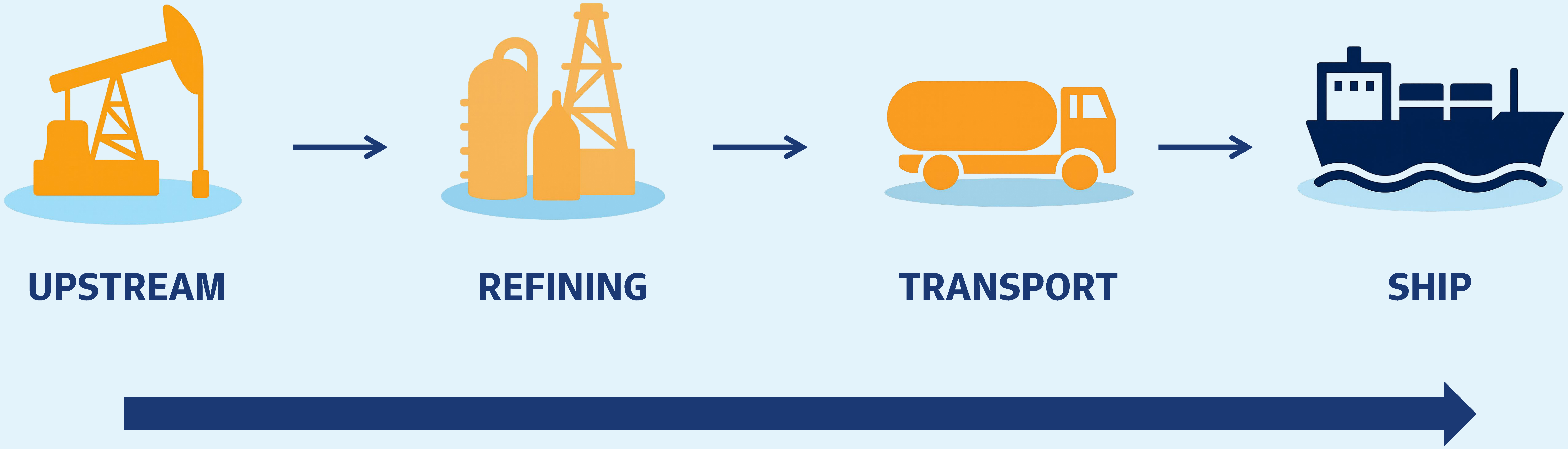
KAPSARC

BUNKER FUEL SUPPLY CHAIN

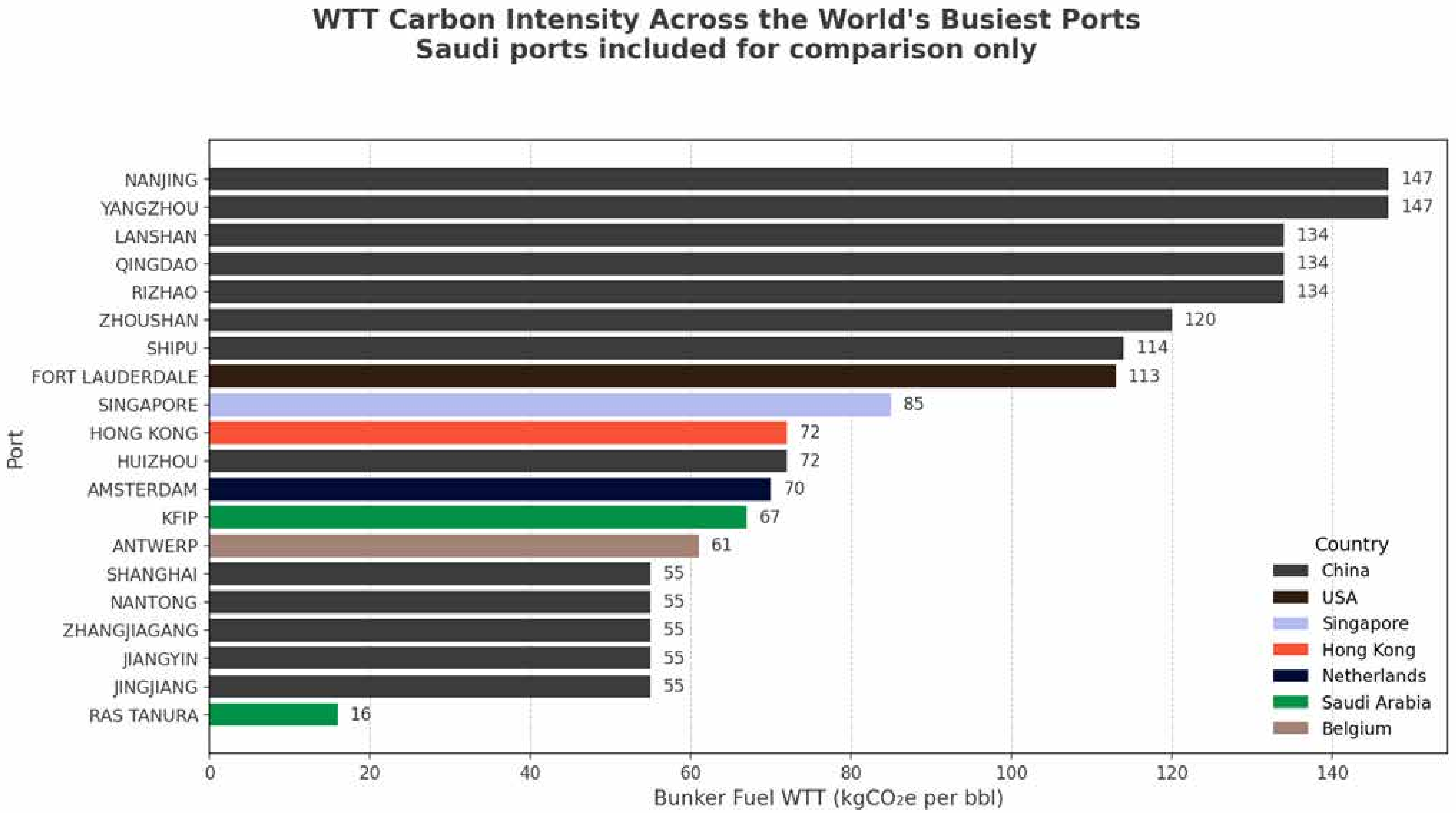
- Bunker fuel used by ships sourced from crude oil via several upstream sources
- Upstream operations include extraction, separation, and transport
- Refineries process crude oil into various petroleum products, including bunker fuel
- Fuel transported to ports for storage and eventual refueling of vessels

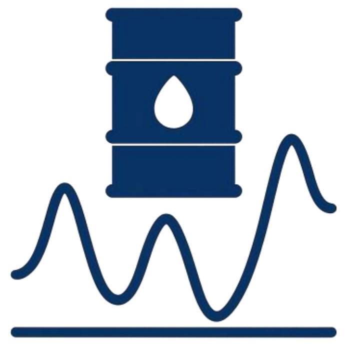


GLOBAL VARIABILITY IN BUNKER FUEL CARBON INTENSITY

- **Wide spread in WtT CI** across ports: ~16 to ~147 $kgCO_2e/bbl$ (**~4 to 26% of WtW CI**)
- **Drivers of upstream variability** (flaring, venting, extraction methods)
- **Refinery configurations** (energy intensity, hydrogen use)
- **Blendstock components** (fuel oil vs distillates)

- **Implication:** OCC operates on top of highly uneven upstream carbon baselines
- **Technology:** Meaningful decarbonization requires progress in both upstream supply chains and onboard operations
- **Policy:** WtT variability should be reflected in assessments to ensure fair and impact-based comparisons





~9x difference

Ras Tanura vs Nanjing illustrates why supply chain decarbonization is crucial

(1) Refinery level CI data source: The Archie Initiative (www.archieinitiative.org)

WHY ROUTE-SPECIFIC OCC ANALYSIS?

Bulk carriers

KSA⟶Asia

- Medium haul
- 96 voyages

China⟶AMS

- Long haul
- 57 voyages

more routes

Voyage profiles differ
ballast/loaded distances, CO2 baselines, cargo

Freight economics
drive break-even feasibility

Engineering footprint
(tanks/modules) depends on route

OCC MODEL & SCENARIO DESIGN

Datasets(1)

- **Vessel name/ID**
- Vessel type
- Ports
- **Cargo**
- **DWT**(2)
- **Ballast/loaded** distances
- **Estimated CO_2** emissions (per leg)
- **Voyage duration**—derived (12 knots average speed)

(1) Source: kpler

(2) DWT = Dead Weight Tonnage

Costs

- **Cargo penalty**—derived
- **CAPEX** (6.85 M$, 2.3 tph, CCF(3)=0.094)
- **Nonfuel OPEX** 19.6 and 38.2 $/t and **offloading** 15 and 34.5 $/t at a capture rate of 1.0 and 2.3 tph, respectively
- **Total cost** = cargo penalty + CAPEX + OPEX + offloading

(3) CCF = Capital Charge Factor

Scenarios

- **Capture rate η** (0.5-0.9)
- **Fuel penalty f** (0.015-0.15)
- **Penalty exhaust ϕ** (bypass vs integrated)
- Full vs loaded-leg penalty
- **Freight rate** $/t cargo (25-50)
- **Mass-balance mode** (captured vs net)
- **Sizing policy** (per-voyage vs per-vessel peak)

5 Charts per Scenario

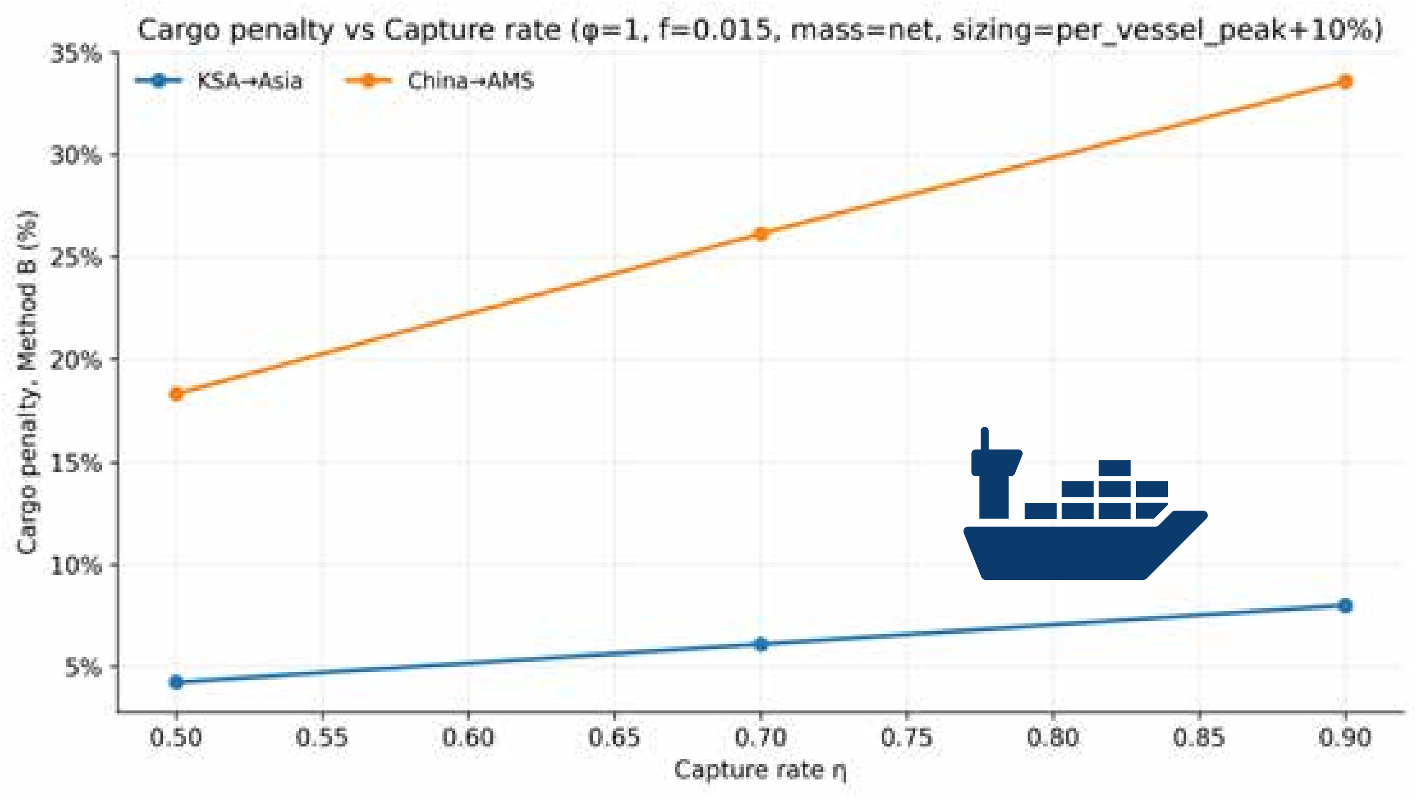
- Cargo penalty vs Capture rate
- BE (cargo) vs Freight
- BE (total cost) vs Freight
- Technology cost breakdown
- Tank/Modules vs Capture rate

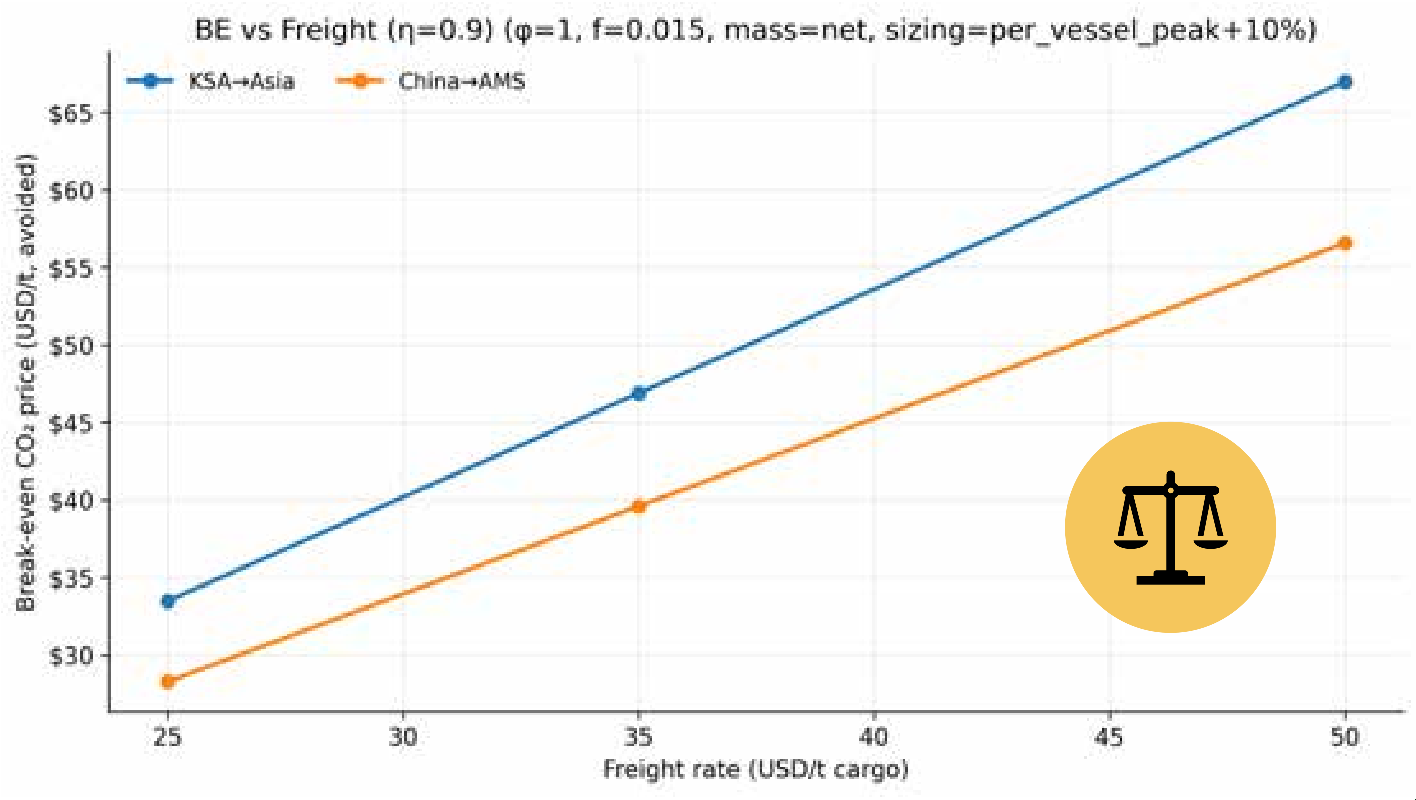
TARGET SCENARIO (ϕ=1, f=0.015, η=0.9)

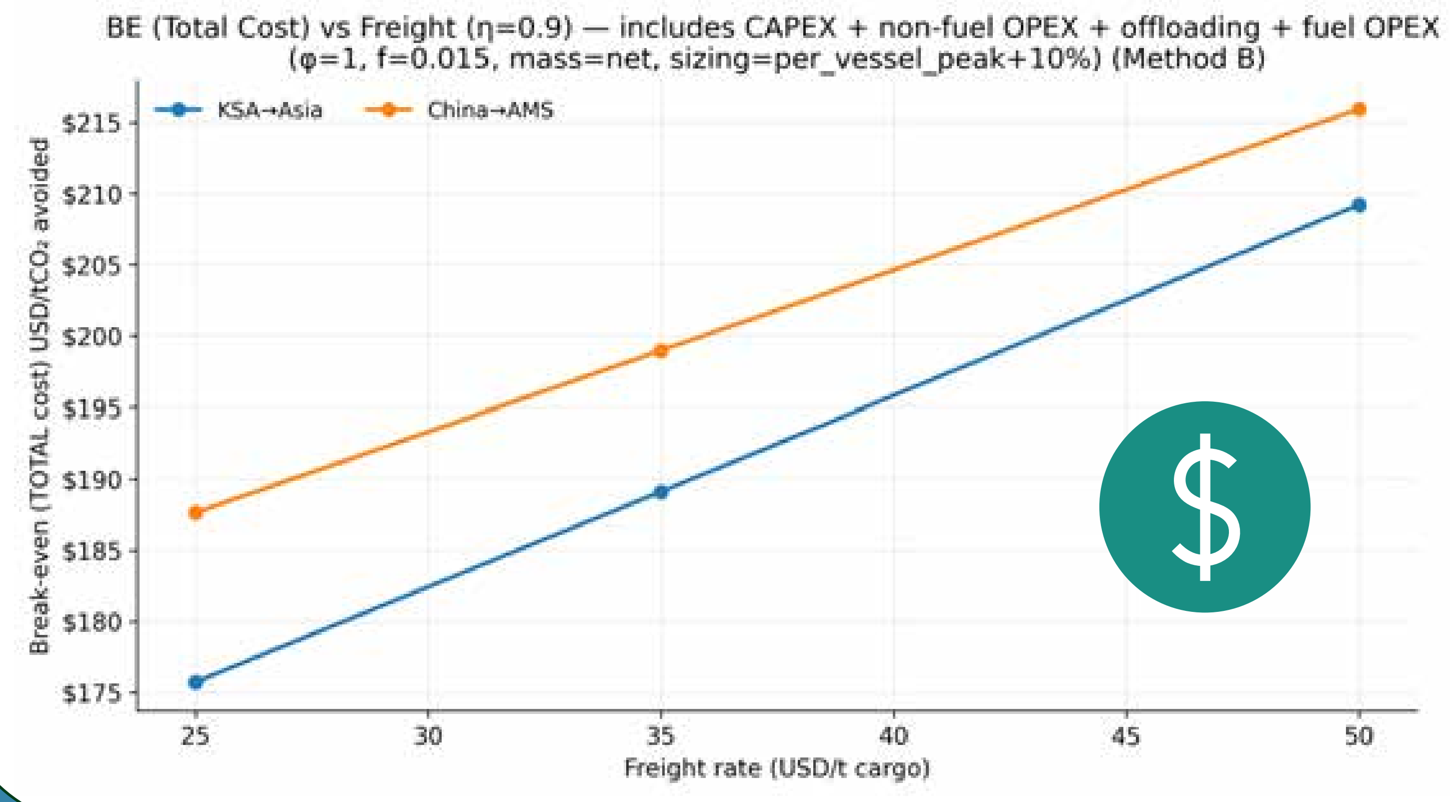
- **Cargo penalty** rises steadily with capture rate
- China⟶AMS (long-haul) shows a **much steeper curve** than KSA⟶Asia
- At η=0.9 the loss is **~34%** for China⟶AMS vs **~8%** for KSA⟶Asia

- Break-even CO_2 price rises with freight rate
- **China⟶AMS shows lower BE than KSA⟶Asia**, despite higher cargo penalty, because **CO_2 avoided per voyage is larger**

- **Break-even CO_2 price climb** once CAPEX and OPEX are included
- **Long-haul China⟶AMS** needs highest CO_2 price, driven by OCC scale
- **Medium-haul KSA⟶Asia** more viable short term, as shorter voyages spread cost more effectively



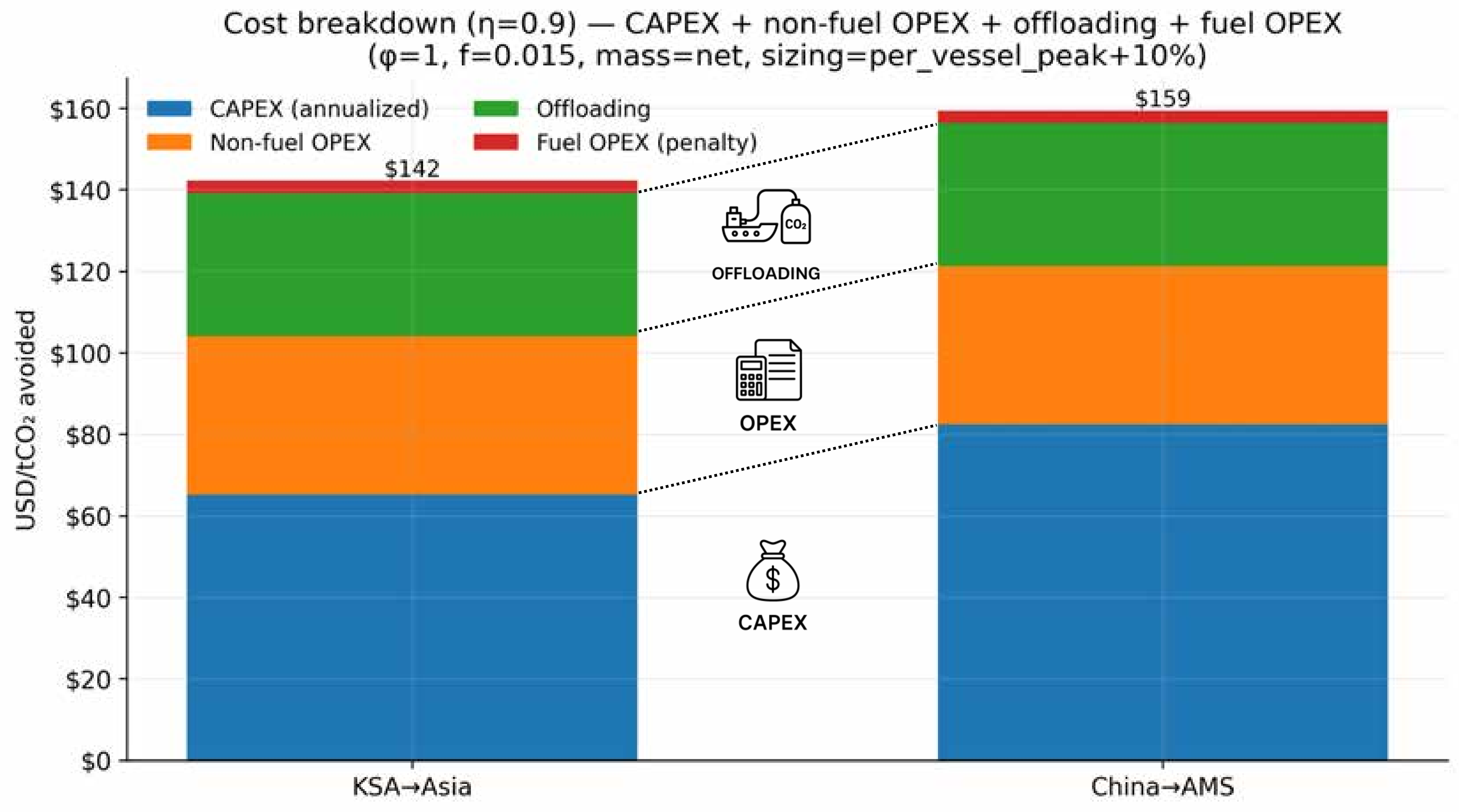


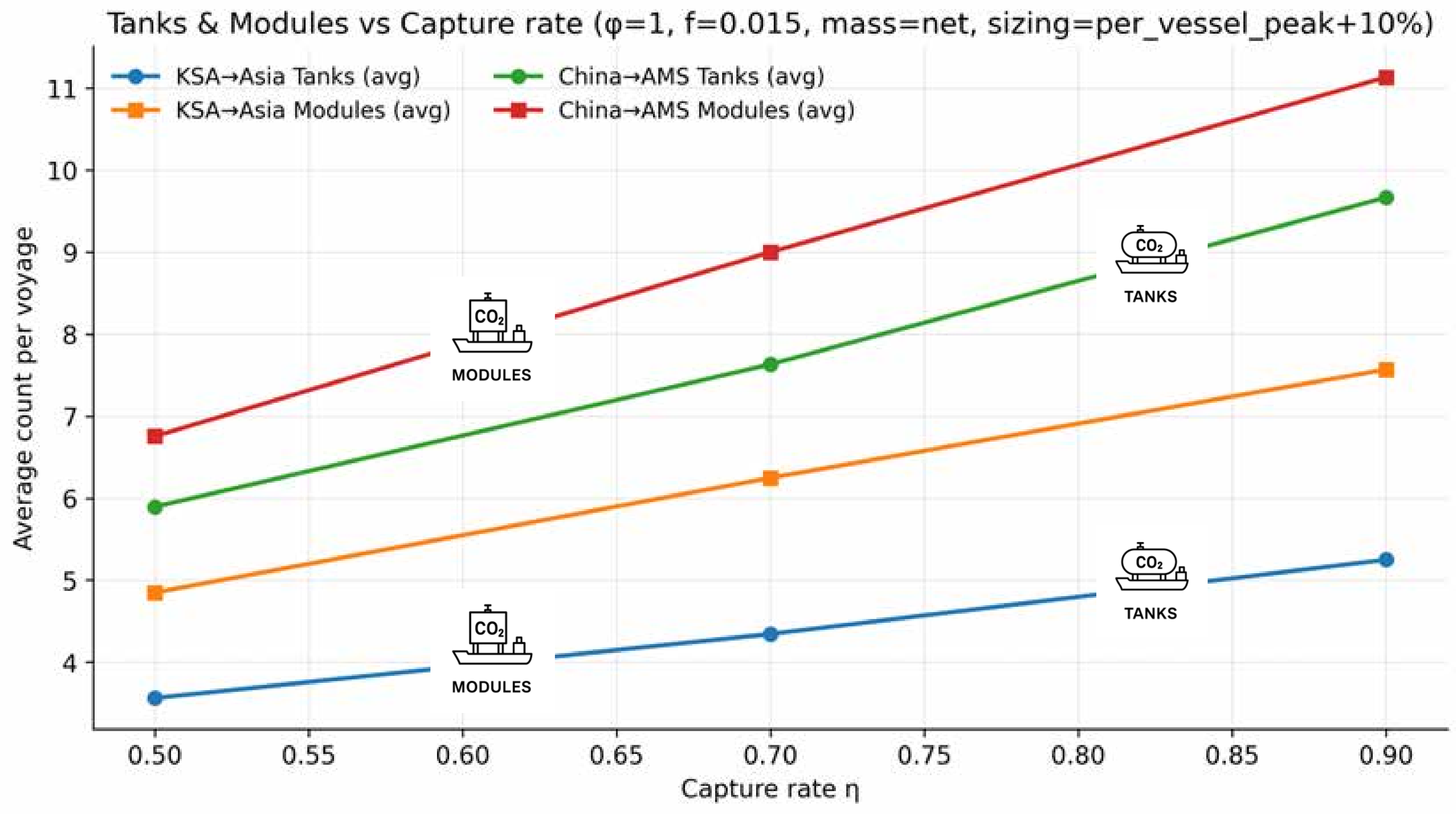


COST BREAKDOWN & SIZING

- **CAPEX dominates the route gap**: ~**$82/t** China⟶AMS vs ~**$65/t** KSA⟶Asia (per tCO_2 avoided)
- **Non-fuel OPEX and offloading match** (**~$39/t** and **~$35/t** each): rate-based from MARAD, normalized per avoided
- **Target offloading cost cuts by increasing transfer rates** (bigger/faster arms, parallel manifolds) so **berth time** drop

- **Long haul installs more equipment** at every η (η=0.9 averages): **modules ~11 vs 8**, **tanks ~10 vs 5** (China⟶AMS vs KSA⟶Asia). This drives the **higher CAPEX per tCO_2 avoided** on the long route
- **Gap widens with higher η**: more capture ⟶ more throughput ⟶ more module/tank replications on long-haul





COMPARATIVE INSIGHTS & TAKEAWAYS

KSA⟶Asia

Cargo penalty
lower (~4-8%)

CAPEX + Offloading dominate

Smaller tank/module sizing

China⟶AMS

Cargo penalty
higher (~18-34%)

CAPEX (higher) dominates

Larger tank/module sizing

Policy levers:

- CAPEX support (carbon pricing/ crediting, CfD(1))
- Standardized offloading frameworks
- Designate more voyages to OCC-equipped vessels (like HOV lanes)
- Deployment scale and standardization

(1) CfD = Contract for Differences (a tool to de-risk investments by setting a floor price for carbon)

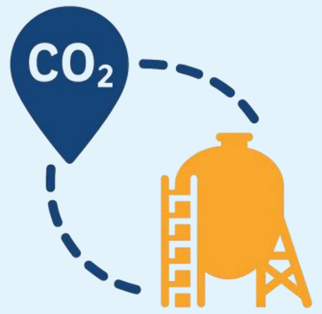
NEXT STEPS IN OUR STUDY

Global Expansion of Model Application

Extend OCC cost model to cover all primary bulk carrier routes worldwide. Incorporate container ships and other major ship classes.

Development of OCC Suitability Index

Create Vessel-Route OCC suitability index at a global scale. Publish results with cost scenarios in a peer-reviewed journal.



CCS Hubs Integration

Connecting ports with major CO2 storage sites to create a scalable, efficient, and cost reducing pathway that transforms OCC into part of a coordinated global decarbonization system.

KAPSARC Well-to-Wake Model

Interactive public tool for onshore & onboard emissions baselining. Enable comparative decarbonization analysis, including OCC.