RESEARCH / EXECUTIVE BRIEFING

BUNKERING DEMAND INTELLIGENCE

From Nationwide Potential Demand to Storage Tank & Bunkering Fleet CAPEX

2023–2025 Full-Port Arrivals (540,741) · 2026 Ulsan Empirical Calibration · 3-Stage Digital Twin

---

38 SLIDES / 28-PAGE CORE REPORT + 10-SLIDE DIGITAL TWIN MASTER EXTENSION

META Integrated AI Platform • Research & Executive Education

Three Strategic Questions for Executive Decision-Makers

Vessel arrival counts are the starting point; investment requires joint analysis of demand, storage, and fleet SLA.

01

Where Is the Demand?

Port-level arrivals & bunkering propensity

→

02

Who Are the Customers?

Vessel type, GT band & operating profile

→

03

How Much Infrastructure?

Demand → Tankage → Fleet & CAPEX

CORE PRINCIPLE Observed arrivals, modeled bunkering calls, and actual BDN sales are strictly distinct evidence tiers.

Counting Only 'Bunkering-Purpose' Arrivals Misses the Market

Vessels refuel during cargo operations or transit; therefore all port arrivals form the candidate population.

Operational Reality

Vessels calling for cargo loading/ discharging, repair, or transit are major bunkering customers.

Observed Public Data

PORT-MIS records port, timestamp, vessel type, GT, and declared purpose, but not actual fuel volume sold.

Analytical Objective

Provides a consistent probabilistic baseline to benchmark port market opportunities without private BDN ledgers.

DISTINCTION Declared Bunkering-Purpose Arrivals ≠ Completed Bunkering Transactions

What Did We Actually Observe?

We strictly separate unified full-port arrival records (Ocean-Going + Coastal) across 31 authorities from model priors.

540,741

3-Yr Ocean (218k) + Coastal (323k) Calls

31 Codes

Port Authority & Jurisdiction Codes

21+ Fields

Arrival, Operation Class & Vessel Spec

OBSERVED · Public Source

Port · Date · Vessel Type · GT · Operation Class (Foreign + Domestic) · Declared Purpose

ASSUMED · Model Parameters

Conditional Bunkering Probability · Mean Stem Size (MT/call) · Scenario Weights

PRINCIPLE All 31 ports apply the unified Ocean-Going + Coastal population while separating observed facts from modeled MT.

540,741 Unified Full-Port Arrivals Observed Over 3 Years

Integrates Ocean-Going (217,578) and Coastal (323,163) vessel calls; 1 port arrival does not equal 1 bunker stem.



HOW TO READ 2025: Foreign 70,867 + Domestic 107,406 · Harbor tugs, barges & bunker craft isolated into low-rate sub-account.

Six-Stage Research & Modeling Pipeline

Raw public arrival ledgers are preserved immutable; model priors are applied in a separate computation layer.

01

Arrival Ingestion

02

Audit & Cleansing

03

Fleet Segmentation

04

Propensity Priors

05

Expected Demand

06

Scenario Bands

MODEL FLOW SOURCE → CLASSIFICATION → PROBABILITY → EXPECTED MT → LOW / BASE / HIGH

Explicit Confidence Tiers Assigned to Every Metric

Observed counts, expected calls, modeled volume scenarios, and external macro benchmarks are governed separately.

Metric Category	Definition & Analytical Basis	Evidence Tier
Arrival Records	Verified PORT-MIS arrival observations (Foreign + Domestic)	FACT
Expected Bunker Calls	Sum of conditional bunkering probabilities across arrivals	ESTIMATE
Potential Demand (MT)	Expected bunkering calls × segment-specific stem size (MT)	SCENARIO
External Energy Stats	Macro scale & fuel-scope cross-check (e.g., KESIS)	REFERENCE

GOVERNANCE Unreconciled prior estimates are never labeled as ACTUAL or OFFICIAL sales.

The Core Calculation Principle Is Transparent

Multiply each segment's conditional refueling probability by its expected stem size per call, then sum.

Expected Demand (MT) = Σ [Arrivals × Bunkering Prob. × Mean Stem (MT)]

Σ denotes independent calculation across each port, vessel type, GT band, and operation class before aggregation.

100

Observed Arrivals

40%

Bunkering Prob.

500 MT

Mean Stem per Call

NUMERIC CHECK 100 Arrivals × 40% Probability × 500 MT/call = 20,000 MT

How Bunkering Probabilities Are Constructed

Prior rules distinguish explicit bunkering-purpose declarations from cargo/transit calls.

A · Declared Bunkering Purpose

Fixed research prior = 100%
6,251 ocean-going calls across 5 port groups (2025)
* Declaration ≠ verified physical BDN delivery

B · Cargo, Repair & Transit Calls

Base Rate × Port × Vessel Type × GT × Purpose Weights
Coastal vessels apply Ulsan empirical propensity ratio (0.873)
Subject to posterior calibration when BDN actuals exist

LIMITATION The 100% rule on declared bunkering arrivals is a modeling convention, not audited transaction accuracy.

Why Segment by Vessel Type, Operation Class, and GT?

Refueling frequency and stem volume vary sharply across ship size, cargo trade, and ocean vs. coastal service.

Port Profile

Hub liner port (Busan) vs. liquid cluster (Ulsan, Yeosu-Gwangyang)

Vessel Type

Distinct fuel appetite across Container, Bulk, Tanker & Coastal craft

Gross Tonnage (GT)

Structural proxy for hull scale & bunker tank capacity tier

Entry Purpose & Scope

Bunkering, cargo work, repair, transit; Ocean-going vs. Coastal

CAUTION Gross tonnage (GT) alone cannot deterministically fix MCR power, tank limit, or actual stem quantity.

Fuel Burned at Sea Differs from Bunker Purchased at Port

Engine fuel burn, single-call stem requirement, and aggregate port demand represent three distinct physical stages.

01

Engine Fuel Burn

MT / day or MT / voyage

→

02

Single-Call Stem Need

Next-leg need + Reserve − ROB

→

03

Port Potential Demand

Arrivals × Selection Prob. × Stem

BOUNDARY Part I focuses on ③ Port Market Demand, while ①·② marine engineering formulas provide physical cross-checks.

Marine Engineering Cross-Check for Fuel Burn & ROB

Standard naval architecture equations used to bound physically plausible stem sizes by vessel class.

Daily Fuel Burn (MT/day) = Power (kW) × Load Factor × SFOC (g/kWh) × 24 ÷ 1,000,000

SFOC = Specific Fuel Oil Consumption (g/kWh). Main engine, auxiliary gensets, and boilers are summed.

Voyage Consumption

Sea daily burn × Sailing days + Port/anchorage auxiliary burn

Required Bunker Stem

max(0, Next-leg fuel requirement + Safety reserve − Current ROB)

INTERPRETATION When real-time vessel ROB and voyage leg distance are unobserved, stem sizes represent scenario priors.

Is Mean Stem per Call an Empirical Fact or Scenario Prior?

We clearly distinguish anchor-implied stem priors from empirically calibrated BDN averages.

Report Formulation

Expected Supply = Bunkering Prob. × Mean Stem per Call
Busan unified mean ~444 MT/call (Foreign ~602 MT · Coastal ~68–145 MT)

Parameter Verification Scope

Vessel-type × GT-band stem lookup matrices
SFOC, ROB & engine spec sensitivity bounds
Provenance of LOW / BASE / HIGH stem multipliers

IMPLEMENTATION Stages 1–3 Digital Twin operationalize calibrated segment parameters, multi-fuel physics, and Erlang-C queueing.

LOW / BASE / HIGH Are Sensitivity Scenarios, Not Point Truths

Structured parameter perturbation experiments evaluate demand range under propensity and stem uncertainty.

LOW

Conservative Demand

BASE

Reference Baseline

HIGH

Hub Expansion Upside

RIGOR LOW and HIGH represent deterministic scenario bounds, not frequentist 95% confidence intervals.

2025 Nationwide Unified Potential Demand (Foreign + Domestic)

Derived by applying segment & operation-class priors across all 31 port authorities in South Korea.

178,273

Observed Arrivals (Foreign+Domestic)

~48,760

Expected Bunkering Calls

14.85M MT

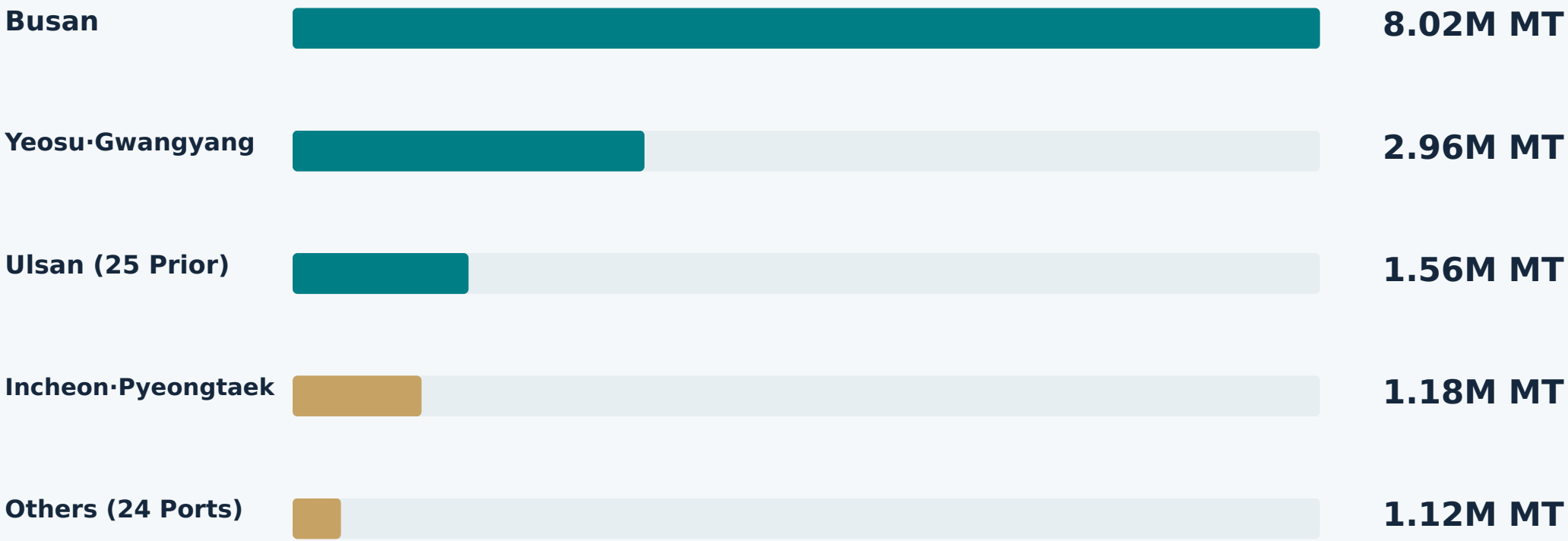
Unified Potential Demand (BASE)

Foreign 70,867 calls (12.90M MT) + Domestic 107,406 calls (1.95M MT) · Overall rate 27.4% · Mean 304.5 MT/call

INTERPRETATION Represents nationwide full-port potential demand for infrastructure planning, not audited BDN sales.

2025 Unified Potential Demand by Major Port Group

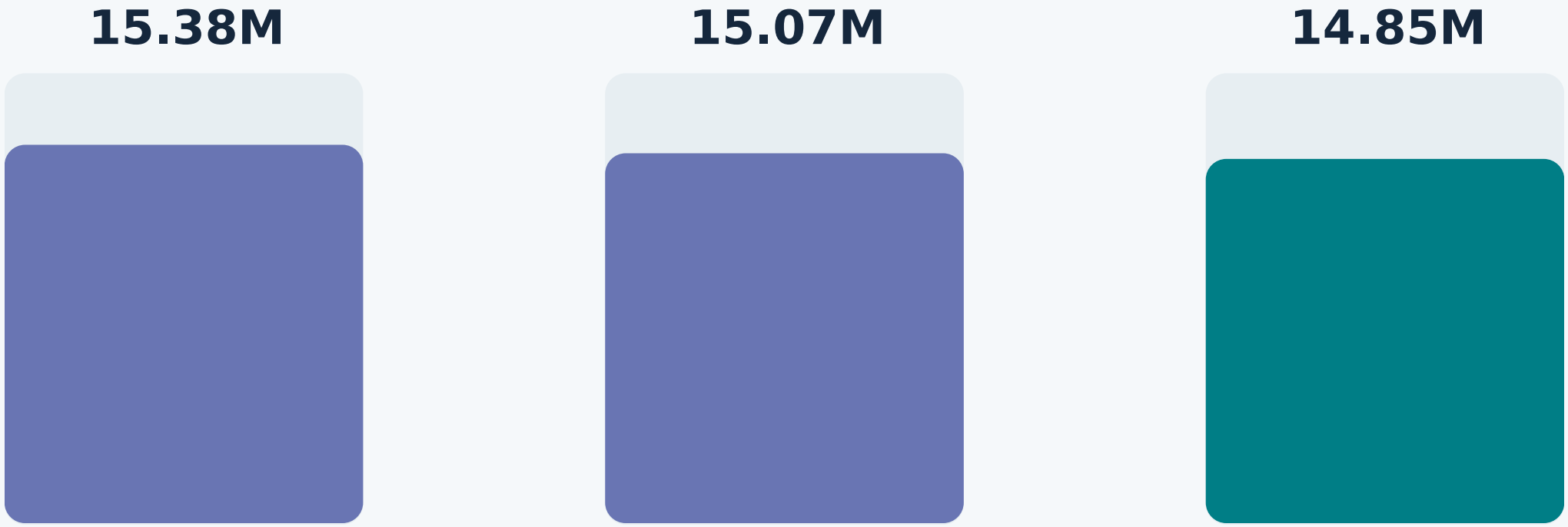
BASE scenario integrating ocean-going vessels and coastal tankers/cargo ships across 5 port groups (14.85M MT).



IMPACT Integrating coastal vessels captures key regional hubs: Daesan (0.18M), Jeju (0.17M), and Masan (0.13M MT).

Three-Year Trajectory of Unified Potential Demand (2023–2025)

Tracks full-port arrival volume alongside modeled baseline bunker demand across 2023–2025.



CAUTION Modeled 2023–2025 demand trajectory reflects arrival mix shifts and must not be cited as historical revenue.

Busan Port Case Study: Foreign + Domestic Decomposition

Decomposes 2025 Busan Port total arrivals of 45,132 vessels (Foreign 22,435 + Domestic 22,702).

Arrival & Bunkering Call Structure

Ocean-Going: 22,435 calls → 12,700 expected stems
Coastal/Domestic: 22,702 calls → 5,380 expected stems
= Unified Expected Calls: ~18,080 stems/yr

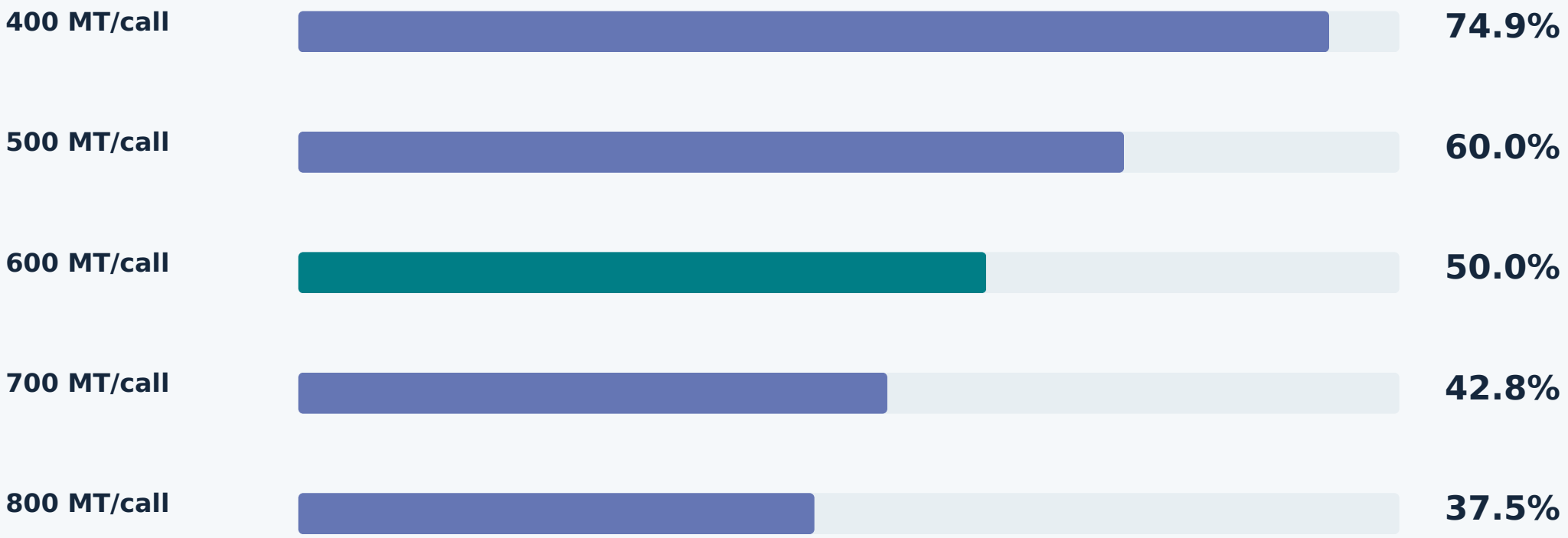
Unified Demand & Stem Structure

Ocean-Going: 7,650,000 MT + Coastal: 371,349 MT
= Unified Baseline Demand: 8,021,349 MT
(Unified Mean Stem: ~443.7 MT/call)

KEY POINT Harbor tugs/barges are isolated at low rates while coastal tankers, feeders, and general cargo are fully captured.

Busan Sensitivity: Required Probability vs. Assumed Stem Size

Required refueling rate among non-bunkering-purpose ocean calls to sustain the 7.65M MT ocean anchor.



CONDITION Holds explicit bunkering-purpose arrivals (2,635 calls) fixed under the Busan ocean-going sensitivity test.

External Macro Energy Statistics Serve as Scale Checks

Macro energy balances differ in vessel scope and fuel coverage from full-port multi-fuel demand.

KESIS Provisional Statistics

2025 International Marine Heavy Fuel Oil
59,911k barrels (~8.93M MT at 0.149 MT/bbl)
Excludes coastal shipping, MGO/DO & LNG

META Unified BASE Model

Full-Port Potential Demand (Foreign + Domestic)
~14.85M MT (Foreign 12.90M + Coastal 1.95M MT)
Encompasses FO, coastal MGO/DO & green fuel energy

NOTE International HFO-only statistics (8.93M MT) and full-port all-fuel demand (14.85M MT) have different boundaries.

Transparent Disclosure of Model Limitations

Mathematical granularity does not substitute for transaction-level BDN reconciliation.

Unlinked BDN Ledgers

Transaction-level BDN delivery notes not linked nationwide

Arrival ≠ Refueling

Declared entry purpose is not proof of fuel delivery

Prior Uncertainty

Unreconciled ports rely on transferred propensity priors

Unobserved ROB

Real-time shipboard ROB & tank ullage limits unavailable

Circularity Risk

Reproducing a prior anchor is not external validation

Regime Shifts

Fuel mix, freight cycles & port alliances evolve over time

ETHICS We prohibit misrepresenting scenario priors as audited prediction accuracy or statistical confidence intervals.

Recommended Decision Uses vs. Prohibited Interpretations

Designed as a strategic capacity & investment decision studio, not a statutory accounting ledger.

Recommended Strategic Uses

- Cross-port market sizing & hub prioritization
- Target customer segmentation by vessel type & GT
- Storage tank, barge fleet & truck bay capacity planning
- Price spread, incentive & green fuel sensitivity testing

Prohibited Interpretations

- Claiming uncalibrated priors as audited BDN sales
- Asserting individual vessel refueling transactions
- Substituting model output for statutory market share
- Claiming validated forecast accuracy without BDN data

How to Read the Interactive Dashboard & Twin Studio

Filtering by Year, Port, Vessel Type, and GT dynamically updates populations and scenario outputs.

01

Select Filters

Year · Port · Vessel Type · GT

→

02

OBSERVED / MODEL

Separate arrivals vs. modeled calls

→

03

Compare Scenarios

Evaluate LOW · BASE · HIGH & Twins

45,132

Busan Unified Arrivals

18,080

Unified Expected Calls

8.02M

Unified Baseline MT

Part I Executive Conclusions

Combines nationwide full-port arrival observations with transparent probability priors and empirical calibration.

- Analyzed 540,741 unified arrivals (2023–2025) and 2026 Ulsan actuals (7,295 ships) in one framework.
- 2025 nationwide unified potential demand is ~14.85M MT (Foreign 12.90M + Coastal 1.95M MT).
- Strictly distinguishes observed vessel arrivals from modeled bunkering calls and volume scenarios.
- Preserves full data lineage as additional ports transition from prior scenarios to BDN calibration.

SUMMARY Bunkering Demand Intelligence = Full-Port Observations + Probabilistic Priors + Transparent Calibration

Data Lineage, References & Reproducibility

Documents the exact provenance of raw arrival records, calibration ledgers, and macro benchmarks.

Internal Pipeline Artifacts

STEP384E · 2023–2025 Foreign+Domestic Master (540,741)
STEP365/399 · Ocean Baseline & Coastal Prior Integration
STEP385E/F · 2026 Ulsan Port Dual-Dimension Calibration
STEP401 · 31-Jurisdiction Unified Rankings & Sensitivity

External References & Glossary

KESIS Monthly Energy Statistics (2026.06, Table 5.4.7)
GT: Gross Tonnage (structural vessel size metric)
MT: Metric Ton (1,000 kg mass unit)
BDN: Bunker Delivery Note (official physical delivery proof)

PROVENANCE All 12 reconciliation CSVs and PORT-MIS packages are downloadable directly from the live portal.

Ulsan Port 2026 Empirical Calibration Benchmark

Completed dual-dimension calibration by reconciling 2026 Ulsan Port full-port official actuals (7,295 vessels).

7,295
Total Arrivals (Foreign+Coastal)

2,912
Confirmed Bunker Calls

958,087 MT
Official Supply (Actual)

39.92%
Empirical Bunkering Rate

Propensity by Scope & Flag (Unified)

Coastal·Korean: 36.04% (1,906) · Foreign: 41.29% (5,389)

Reconciliation Boundary

Classified 2,727 + Unmapped 185 = 2,912 Calls
Zero double-counting on 958,087 MT total

EVIDENCE TIER 2023–2025 nationwide prior scenarios and 2026 Ulsan official calibrated actuals are distinct tiers.

Ulsan 2026 Vessel-Segment Calibration Ledger

Reconciles 7 commercial vessel groups (2,727 calls) and separate review craft (185 calls) to exact official totals.

Vessel Group	Est. Arrivals	Bunker Calls	Bunker Rate	Supply (MT)
Crude Tanker	337.8	94	27.82%	61,415
Product Tanker	2,973.9	975	32.79%	295,647
Chemical Tanker	1,122.1	679	60.51%	143,944
LPG Tanker	402.7	192	47.68%	73,231
General Cargo	670.9	515	76.76%	258,491
Dry Bulk Carrier	337.2	232	68.80%	111,867
Other Commercial	706.6	40	5.66%	13,492
Unmapped Review Craft	743.8	185	24.87%	Included in Total
Official Total	7,295	2,912	39.92%	958,087

RECONCILED Unmapped 185 calls (tugs, bunker barges, PCC) are included inside 958,087 MT without double counting.

Synchronized Platform Operations & Verifiable Datasets

Live dashboard views, downloadable CSVs, and digital twin simulators share a single source of truth.

Live Dashboard Verification

2026 Ulsan Benchmark Mode Switch
Arrivals 7,295 / Bunker Calls 2,912
Supply 958,087 MT / Mean 329.0 MT
Real-time Korean vs. Foreign flag comparison

12 Downloadable Research CSVs

Master reconciliation & official anchors
Vessel-type empirical calibration ledger
Nationality & Foreign/Domestic projections
31-port unified rankings & sensitivity matrices

SSO INTEGRATION Central portal SSO connects the demand dashboard directly to the 3-Stage Infrastructure Digital Twin.

Unified Full-Port (Foreign + Domestic) Mathematical Framework

All 31 ports operate on the identical Ocean-Going + Coastal population; ports differ only in calibration stage.

UNIFIED FULL-PORT DEMAND EQUATION (GOVERNING ALL 31 PORT JURISDICTIONS)

$$D^{Total}_p = \eta_p \cdot \Sigma_{v=1..8} \Sigma_{g \in \{FOREIGN, DOMESTIC\}} [N_{p,v,g} \times P^{0}_{p,v,g} \times S^{0}_{p,v,g}]$$

• p: Target Port • v: 8 Vessel Groups • g: Operation Scope (FOREIGN + DOMESTIC Unified) • η_p: Empirical Calibration Factor

01 · 30 National Ports — Unified Full-Port Prior Mode

• Full Population: 2023–2025 Foreign (217,578) + Domestic (323,163) = 540,741 arrivals
• 2025 Major Hubs: Busan 45,132 calls (8.02M MT) · Yeosu-Gwangyang 32,497 (2.96M MT)
• Harbor Craft Filter: Tugs, barges & service craft isolated into low-rate auxiliary account
• Coastal Priors: Ulsan empirical domestic/foreign ratio (0.873) & GT-tiered stems (68–245 MT)
• Twin Integration: Coastal DO tankage & TTS truck loading bays captured across all ports

02 · 2026 Ulsan Port — Posterior Empirical Calibrated Mode

• Identical Engine: Exact same full-port equation reconciled to official UPA BDN actuals
• Unified Population: Foreign 5,389 ships (73.9%) + Domestic/KR 1,906 ships (26.1%) = 7,295
• Propensity Gap Verified: Domestic/KR 36.04% vs. Foreign 41.29% (+5.25%p empirical gap)
• Zero-Error Match: 2,912 bunker calls (2,727 commercial + 185 review) · 958,087 MT exact
• Seamless Evolution: Other ports switch to calibrated mode via η_p as BDN data arrives

UNIFIED SCOPE Every port computes demand, tankage, and fleet from unified Foreign+Domestic arrivals (540,741); BDN updates η_p.

From Demand Forecast to CAPEX: 3-Stage Decision Pipeline

Translates 'How much fuel will be sold?' into 'How many tanks, barges, LNGBVs, and $M CAPEX are required?'

STAGE 01 · Market & Economics Layer
Demand & Price Elasticity Twin

- Key Inputs:
  - Segment×Scope arrivals (N_{p,v})
  - Price spread vs. Singapore (ΔP)
  - Foreign share & port incentives (ρ)
- Core Engine:
  - Conditional propensity elasticity
  - Real-time Monte Carlo funnel gate
- Handoff to Stage 2:
  - ➔ Annual baseline demand D_p (MT/yr)
  - ➔ Expected bunker calls C_p (Calls/yr)

STAGE 02 · Thermodynamics & Storage
Multi-Fuel Volumetric & Tank Twin

- Key Inputs:
  - 4-fuel energy mix (FO·DO·LNG·MeOH)
  - Safety buffer days (τ_buf = 10–14d)
  - Peak factor (1.25) · Fill limit (85%)
- Core Engine:
  - Iso-energy mass & volume conversion
  - Segregated modular tank ceiling K*_f
- Handoff to Stage 3:
  - ➔ Fuel mass M_f & required m³ V^req_f
  - ➔ Dedicated modular tanks K*_f (Units)

STAGE 03 · Queueing & CAPEX Layer
Erlang-C Fleet & Spatial CAPEX Twin

- Key Inputs:
  - Annual workable days (D_op = 320d)
  - Turnaround time by fuel (4.2h–12.5h)
  - Max vessel waiting SLA (α_SLA ≤ 5%)
- Core Engine:
  - M/M/c Erlang-C knee-point solver
  - Chemical tank retrofit discount (θ=0.45)
- Executive Outputs:
  - ➔ Optimal barges & LNGBVs c*_f
  - ➔ Port zone siting & Total CAPEX ($M)

END-TO-END SEQUENTIAL STATE-TRANSITION MAPPING

$$(N^0_{p,v},\ \Delta P_{sp},\ \varphi_{FOR}) \xrightarrow{\text{[Stage 1]}} (D_p,\ C_p) \xrightarrow{\text{[Stage 2: } w_f,\ \tau_{buf}\text{]}} \{V^{req}_f,\ K^*_f\} \xrightarrow{\text{[Stage 3: } \alpha_{SLA}\text{]}} \{c^*_f,\ CAPEX_p\}$$

AUTO HANDOFF Stage 1 demand (MT) and calls automatically feed Stage 2 modular tank sizing and Stage 3 Erlang-C fleet & CAPEX.

Dual-Dimension Demand Estimation & Monte Carlo Funnel

Segment-level disaggregation is essential because refueling frequency (27.8%–76.8%) and stem size (212–653 MT) diverge.

VESSEL-SEGMENT MICRO DEMAND FORMULA

$$C_p = \Sigma_v (N_{p,v} \cdot P_{p,v}), \quad D_p = \Sigma_v (N_{p,v} \cdot P_{p,v} \cdot S_{p,v})$$

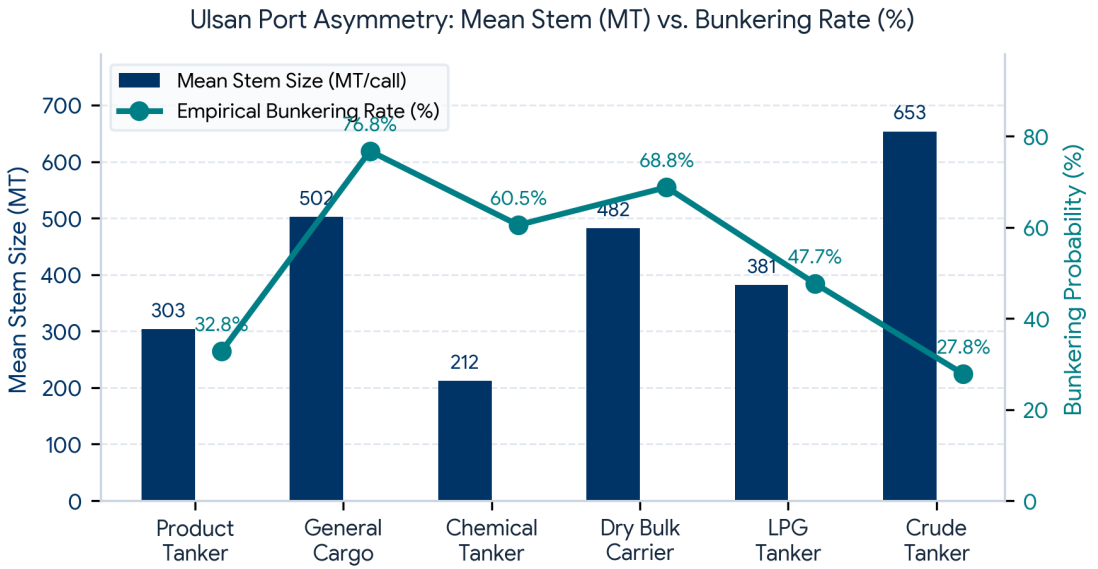
• $N_{p,v}$: Unified segment arrivals • $P_{p,v}$: Refueling prob. • $S_{p,v}$: Mean stem (MT)

Ulsan 2026 Empirical Verification & Funnel Mechanics

① Product Tanker (High-Frequency Medium Stem)
2,973.9 ships × 32.79% prob. = 975 calls × 303.2 MT = 295,647 MT (30.9% share)

② General Cargo Vessel (High-Propensity Large Stem)
670.9 ships × 76.76% prob. = 515 calls × 501.9 MT = 258,491 MT (27.0% share)

③ Real-Time Monte Carlo Probability Funnel
Simulates arriving vessels passing probability gates (39.92%) to split into active bunkering callers (2,912) vs. cargo-only transits (4,383).



▶ Chart Insight: Chemical tankers refuel frequently (60.5%) in small stems (212 MT), whereas crude tankers refuel less often (27.8%) but lift massive stems (653.4 MT). Disaggregated simulation captures this structural asymmetry accurately.

ZERO BIAS Eliminates macro aggregation bias and reconciles 100% with Ulsan Port's 8-segment official BDN benchmark.

Price Spread Elasticity (ΔP) & Port Incentive Simulation

Quantifies discretionary bunker callers captured via price competitiveness against Singapore/Zhoushan and port rebates.

CONDITIONAL BUNKERING PROPENSITY ELASTICITY FUNCTION

$$P_{p,v} = \text{clip}_{[0.03, 0.92]} \left(P^{0}_{p,v} + \beta_{flag} \cdot \Delta\varphi_{FOR} - \beta_{price} \cdot \Delta P_{sp} + \rho_{inc} \right)$$

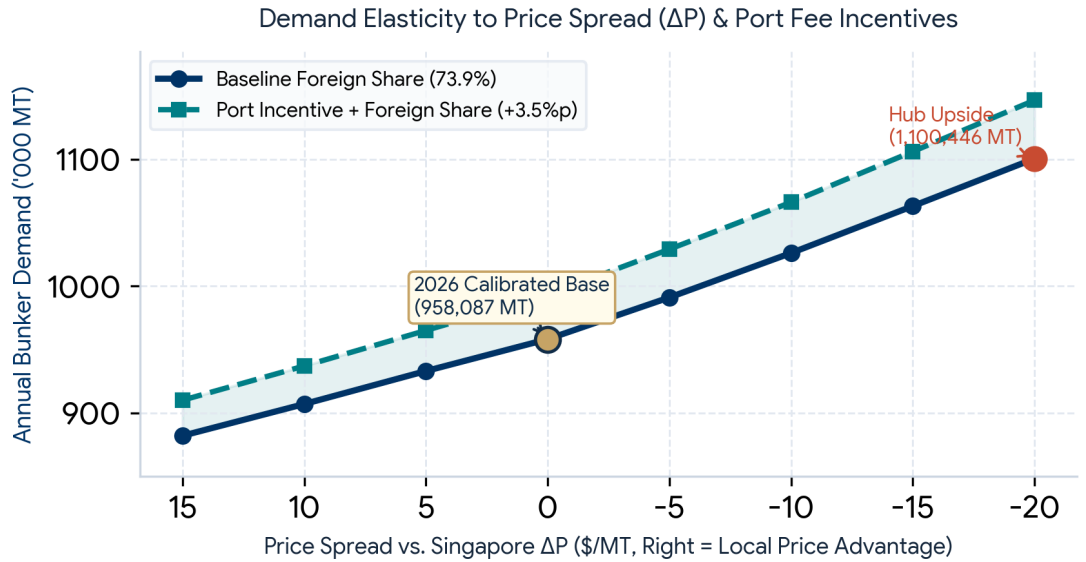
• ΔP_{sp} = $P_{Local} - P_{Singapore}$ ($/MT) • $\Delta\varphi_{FOR}$: Foreign share shift • ρ_{inc}: Rebate (%p)

Mechanics of the Three Market & Policy Control Levers

01 · Bunker Price Spread vs. Competing Hubs ($-\beta_{price} \cdot \Delta P_{sp}$)
When local bunker prices undercut Singapore ($\Delta P_{sp} < 0$), ocean-going vessels divert for bunker arbitrage, expanding conditional capture probability $P_{p,v}$.

02 · Foreign Ocean-Going Share Expansion ($+\beta_{flag} \cdot \Delta\varphi_{FOR}$)
Foreign-flag ships exhibit +5.25%p higher refueling propensity (41.29% vs. 36.04%), lifting overall port capture rates as global liner/tanker calls grow.

03 · Port Dues & Anchorage Rebate Incentives ($+\rho_{inc}$)
Waiving port/anchorage dues for bunker-only callers shifts marginal capture upward.



▶ Simulated Scenario Band (Ulsan Benchmark):

• Conservative (Low): 937,417 MT • Empirical Base: 958,087 MT

• Hub Upside (High): 1,100,446 MT (+142,359 MT net gain, ~+$92M/yr market revenue)

HUB UPSIDE Combining a -$15/MT price advantage with port fee rebates expands Ulsan demand from 958k MT up to 1.10M MT.

Multi-Fuel Thermodynamics & The Law of Volumetric Expansion

Transitioning to green fuels (LNG & Methanol) requires 2.08× to 2.45× more onshore storage tank volume for equal energy.

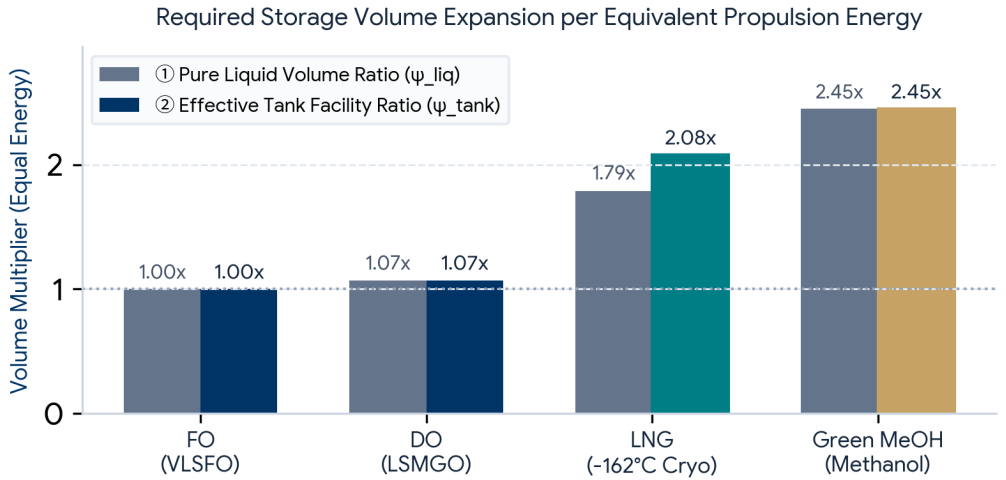
EQUIVALENT PROPULSION ENERGY & DUAL VOLUMETRIC EXPANSION

$$M_f = D_p \cdot w_f \cdot (LHV_{FO} / LHV_f) , \quad \psi^{liq}_f = \kappa^{mass}_f \cdot (\rho_{FO} / \rho_f)$$

Effective Tank Multiplier: $\psi^{tank}_f = \psi^{liq}_f \times (\eta_{usable,FO} / \eta_{usable,f})$ [Cryogenic Heel & Ullage]

Fuel Type	LHV (MJ/kg)	Mass (κ_mass)	Density (t/m³)	① Liquid Vol. Ratio	② Facility Tank Ratio
FO (VLSFO)	40.5	1.00×	0.96	1.00×	**1.00×**
DO (LSMGO)	42.6	0.95×	0.85	1.07×	**1.07×**
LNG (-162°C)	48.2	0.84×	0.45	1.79×	**2.08×**
Green MeOH	20.0	2.02×	0.79	2.45×	**2.45×**

* Engineering Note: LNG has low liquid density (0.45 t/m³) and requires a permanent 10% cryogenic cooling heel plus BOG headspace (2.08× tankage); Methanol has half the LHV, requiring 2.45× volume.



▶ Overcoming Infrastructure Blind Spots:
Sizing green bunkering terminals based on legacy HFO rules will cause severe >50% storage deficits after 2030.
Stage 2 Twin prevents under-sizing via thermodynamic physics.

DUAL RATIO Reconciles pure liquid volume ratio (LNG 1.79×) with effective cryogenic tank volume (LNG 2.08×) including 10% heel & BOG.

Segregated Modular Tank Sizing & Chemical Cluster Retrofit

FO, DO, LNG, and Methanol require incompatible temperatures and metallurgy, mandating dedicated modular tank farms.

DEDICATED MODULAR TANK SIZING EQUATION (INDEPENDENT BY FUEL)

$$V^{req}_f = [\,(M_f / 365) \cdot \tau_{buf} \cdot \zeta_{peak}\,] / (\rho_f \cdot \eta_{fill}), \quad K^*_f = \lceil V^{req}_f / u_f \rceil$$

• τ_buf: Buffer days (12d) • ζ_peak: Seasonal peak (1.25) • η_fill: Safe filling limit (0.85)

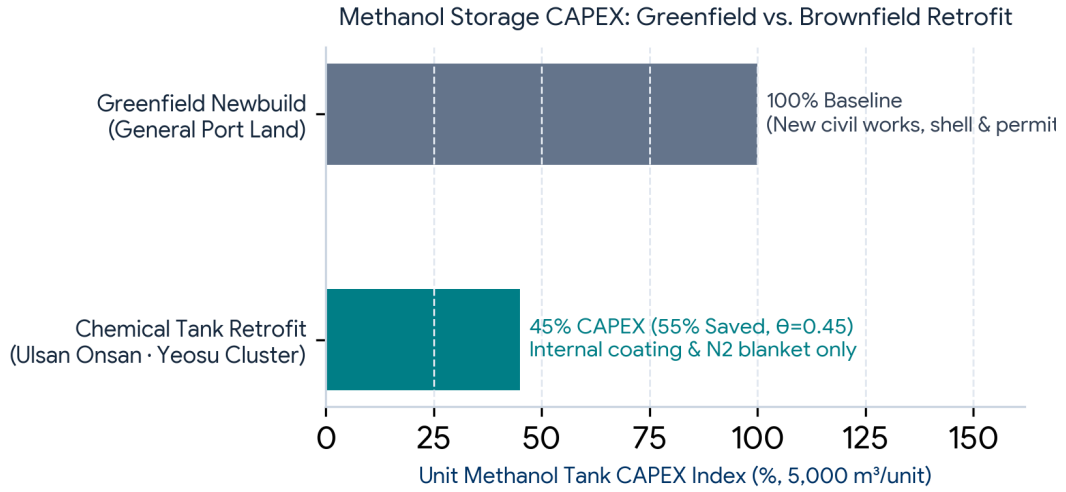
Standard Modular Tank Units (u_f) & Numerical Verification

- FO Tank Farm (u_FO = 10,000 m³/unit): Heated (50–60°C) carbon-steel tanks
- DO Tank Farm (u_DO = 3,000 m³/unit): Ambient high-turnover coastal MGO tanks
- LNG Tank Farm (u_LNG = 15,000 m³/unit): −162°C 9% nickel-steel cryogenic tanks
- MeOH Tank Farm (u_MeOH = 5,000 m³/unit): N2-blanketed specialty coated tanks

▶ Numerical Check (Ulsan 2030 at 23% LNG energy share):

M_LNG = 1,085,000 × 0.23 × 0.84 = 209,622 MT/yr

V^req_LNG = (574.3 × 12 × 1.25) ÷ (0.45 × 0.85) = 22,522 m³ → 2–3 × 15k m³ tanks



▶ Why Ulsan & Yeosu-Gwangyang Lead in Green Methanol:
Cryogenic LNG tanks require 100% greenfield builds, whereas ambient liquid Methanol can retrofit commercial chemical tanks (θ_retro = 0.45), saving 55% in CAPEX and accelerating permitting by years.

CLUSTER EDGE Retrofitting existing liquid chemical tanks in Ulsan Onsan & Yeosu cuts Methanol storage CAPEX by 55% vs. greenfield.

Three Delivery Modes (STS·TTS·PTS) & Non-Deductibility Theorem

Distinguishes delivery logistics by vessel berth/anchorage location and sizes onshore storage independently of barges.

Delivery Mode	Target Vessel Location	Operational Process (Onshore Tank → Receiving Ship)	Primary Fuels & Assets
STS (Ship-to-Ship) **Offshore Barge/LNGBV**	Outer anchorage ships or berthed liners (SIMOPS)	Bunkering barges or cryogenic LNGBVs load at terminal jetties and moor alongside receiving ships at anchorage or waterside berths for SIMOPS	FO (Bunker Barges) LNG (Dedicated LNGBV) MeOH (Chemical Barges)
TTS (Truck-to-Ship) **Tank Lorry Delivery**	Coastal & small vessels at general cargo piers	20–30 MT tank lorries load at onshore Truck Loading Bays and drive directly onto pier aprons for hose-connected small-lot refueling	DO (Coastal LSMGO) High-frequency small stems
PTS (Pipe-to-Ship) **Direct Jetty Pipeline**	Ships berthed directly at energy/chemical jetties	Direct high-flow transfer from onshore storage tanks via jetty pipelines and marine loading arms without intermediate barges or trucks	Onsan Chemical Pier (MeOH) Ulsan KET Energy Pier (LNG)

Theorem ① · Immediate Reloading Inventory Guarantee

When a 7,500 m³ LNGBV or barge returns empty after offshore delivery, onshore tanks must hold
immediately pumpable liquid inventory ($V_{inv} \geq V_{parcel}$) to enable continuous back-to-back sorties.
Deducting vessel hold capacity from onshore tankage causes reloading delays and terminal stock-outs.

Theorem ② · Storm Buffer & Ocean Carrier Demurrage Defense

When gale warnings halt offshore STS operations for 3–4 days, barges remain immobilized fully laden.
Independent onshore buffer capacity (10–14 days) is essential to receive incoming refinery pipeline flows
or 170k m³ ocean LNG carriers without incurring severe vessel demurrage penalties.

DESIGN RULE Barges & LNGBVs are mobile delivery shuttles while onshore tanks are static safety buffers; never deduct barge capacity.

Turnaround Breakdown & Erlang-C Queueing (M/M/c) Optimization

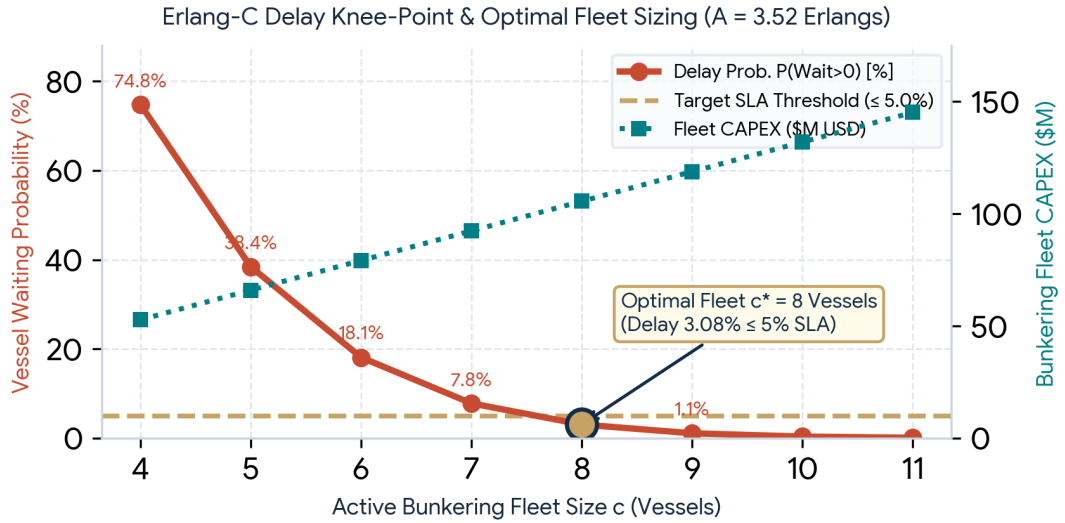
Identifies the exact fleet knee-point (c*) for $70M LNGBVs (12.5h/call) and barges to satisfy SLA ≤ 5% without overbuilding.

M/M/c ERLANG-C WAITING PROBABILITY & INTEGER FLEET OPTIMIZATION

$$P_W(c) = \left[(A^c / c!) \cdot c/(c-A) \right] / \left[\Sigma_{k=0..c-1} (A^k/k!) + (A^c/c!)\cdot c/(c-A) \right] \le \alpha_{SLA}$$

Offered Load $A_f = \lambda_f \cdot \bar{s}_f$ (Erlangs) , Optimal Fleet $c^*_f = \min \{ c \in Z+ \mid P_W(c) \le 5\%, A_f/c \le 0.86 \}$

Single-Sortie Process Step	DO Barge	FO Barge	MeOH Barge	LNGBV
① **Transit & Alongside Mooring**	1.2 h	2.0 h	2.0 h	**2.2 h**
② **Hose Hookup & Cryo Cool-down**	0.5 h	1.0 h	1.5 h	**2.8 h**
③ **Main Pumping & BOG Return**	1.8 h	4.0 h	4.0 h	**4.5 h**
④ **Line Drain, N2 Purge & Unmoor**	0.7 h	1.5 h	2.0 h	**3.0 h**
Total Service Time ($\bar{s}_f$)	**4.2 h**	**8.5 h**	**9.5 h**	**12.5 h**



▶ Curve Reading (Empirical Load A = 3.52 Erlangs):

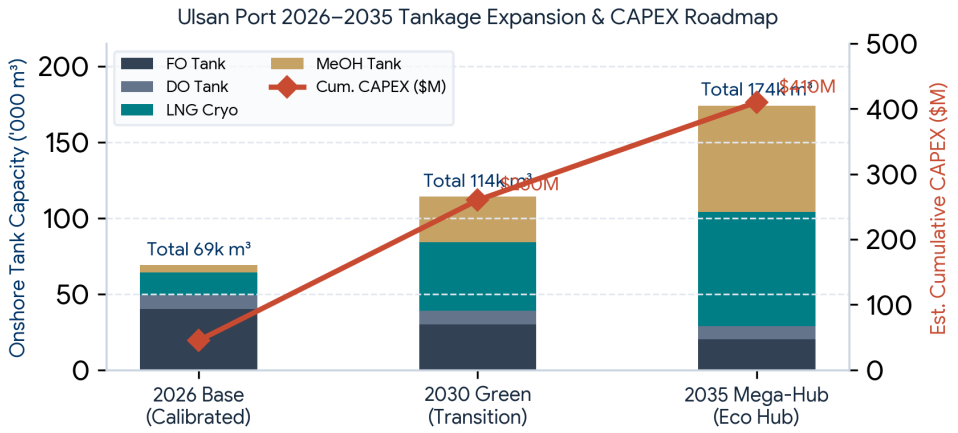
- 5 vessels: 38.4% delay risk (severe anchorage congestion & port diversion)
- 7 vessels: 7.77% delay → 8 vessels drops sharply to 3.08% (Meets SLA ≤ 5%!)
- Optimal fleet c* = 8 vessels avoids both bottlenecks (≤7) and idle CAPEX (≥9).

OPTIMIZATION The golden knee-point where waiting probability P_W(c) first drops below SLA ≤ 5% yields the optimal fleet c*.

Ulsan Port 2026–2035 Energy Transition Infrastructure & CAPEX Roadmap

Quantitative simulation across 2026 Empirical Base, 2030 Green Transition, and 2035 Eco Mega-Hub.

Key Design Metric	2026 Base (Calibrated)	2030 Green (Transition)	2035 Mega-Hub (Eco Hub)
Propulsion Demand (Bunkering Calls)	958,087 MT (2,912 Calls)	1,085,000 MT (3,240 Calls)	**1,280,000 MT (3,790 Calls)**
Multi-Fuel Energy Mix (FO/DO/LNG/MeOH)	72% / 22% 5% / 1%	48% / 14% 23% / 15%	**25% / 10% 35% / 30%**
Installed Onshore Storage Tankage	69,000 m³ (FO4·DO3· LNG1·MeOH1)	114,000 m³ (+65%) (FO3·DO3· LNG3·MeOH6)	**174,000 m³ (+152%) (FO2·DO3· LNG5·MeOH14)**
Optimal Fleet Size (SLA ≤ 5% Target)	FO/DO Barges: 6 + LNGBV: 1	Barges: 6 + Chem: 2 + LNGBV: 2	**Barges: 4 + Chem: 4 + LNGBV: 3**
Est. Cum. CAPEX (w/ Onsan Retrofit)	Existing Assets (Minimal Newbuild)	$245M – $275M ($38M Retrofit Saved)	**$390M – $430M (Full Mega-Hub)**



TOTAL INFRASTRUCTURE CAPEX OBJECTIVE

$$CAPEX_p = \Sigma_f [\ \theta_{retro} \cdot (V_f / 10^4) \cdot \pi^{tank}_f + C^*_f \cdot \pi^{vessel}_f\ ] + B_{bay} + \Pi_{PTS}$$

- Unit CAPEX: LNGBV ~$70M/ship, Barges ~$13.2–18M/ship
- Onsan Methanol tank retrofit (θ_{retro}=0.45) lowers upfront capital barrier

KEY INSIGHT By 2035 propulsion energy demand grows +33.6%, but LNG/MeOH volumetric expansion requires +152% onshore tankage.

Ulsan Port Spatial Masterplan & Executive Decision Guide

Aligns fuel-specific storage and berth siting with industrial cluster assets to eliminate redundant CAPEX.

ZONE 01 · FO (VLSFO / HSFO)

Onsan & New Port South Breakwater Barge Base

- Shortest marine transit to outer anchorages (E-1 to E-3) for 4,000 DWT STS barges
- Direct refinery pipeline feed minimizes barge turnaround cycle

ZONE 02 · DO (Marine Gas Oil · Coastal Focus)

Ulsan Main Port General Pier Truck Loading Bays (TTS)

- Concentrates TTS tank-lorry bays at high-frequency coastal & small cargo piers
- Replaces costly offshore barge sorties for small-lot MGO deliveries

ZONE 03 · LNG (-162°C Cryogenic Gas)

Ulsan New Port North Energy Terminal (Linked to KET)

- Leverages Korea Energy Terminal (KET) large LNG tanks & dedicated PTS jetty
- Minimizes LNGBV reloading time and supports large liner SIMOPS

ZONE 04 · Green Methanol

Onsan National Industrial Complex Liquid Chemical Piers

- Retrofits commercial chemical tanks (55% CAPEX saved) + direct PTS jetty pipelines
- Delivers Northeast Asia's most cost-competitive green methanol supply

01 · Unified Data & Model Consistency

Integrates Observed Facts, Full-Port Priors (540,741), and Ulsan Calibrated Actuals in one engine.

02 · Thermodynamic & Queueing Rigor

Couples multi-fuel LHV, density & cryogenic heel physics with M/M/c Erlang-C fleet optimization.

03 · Real-Time Policy & CAPEX Studio

Instantly tests price spreads, port rebates, and green fuel mixes on tankage, fleet & CAPEX ($M).

CONCLUSION META Bunkering Digital Twin unifies Full-Port Demand (Stage 1), Multi-Fuel Tankage (Stage 2), and Erlang-C CAPEX (Stage 3).