

EU ETS and Transshipment Hub Competition: A Resource-Based Systems Thinking Assessment of Cai Mep-Thi Vai and Singapore

Nguyen Thi Thu Chung^{1,*}, Phuong Kim Hoang Vuong¹, Ho Truc Ngoc¹, Le Quynh Anh¹

¹University of Transport Ho Chi Minh City, Ho Chi Minh City, Vietnam

Abstract

The extension of the EU Emissions Trading System (EU ETS) to shipping raises the compliance cost of calling vessels. This study examines how Vietnam's renewable energy endowment and Direct Power Purchase Agreement (DPPA) mechanism shift the competitive position of Cai Mep-Thi Vai (CM-TV) against Singapore, combining the Resource-Based View, the TOE framework, and Causal Loop Diagramming. CM-TV holds a domestic energy advantage that Singapore has not been able to replicate domestically, while Singapore leads in technology and organization but depends on imported green fuel. A cost simulation shows CM-TV trails Singapore on the EU ETS component alone but gains a net saving through FuelEU Maritime's lower-cost domestic fuel, though congestion and certificate verification lag can erode it. The paper proposes a port-energy integration model, anchored by a green economic zone at CM-TV, to convert this window into a durable position within a dual-hub routing strategy.

Keywords: EU ETS, Systems Thinking, Resource asymmetry, Compliance routing

Received on 13 September 2026; accepted on 14 October 2026; published on 26 October 2026

Copyright © 2026 Nguyen Thi Thu Chung *et al.*, licensed to EAI. This is an open access article distributed under the terms of the [CC BY-NC-SA 4.0](#), which permits copying, redistributing, remixing, transformation, and building upon the material in any medium so long as the original work is properly cited.

doi: 10.4108/tsoe.15115

1. Introduction

The maritime transport sector is changing under the expansion of the European Union Emissions Trading System (EU ETS) to shipping from January 2024. The EU ETS places a direct price on carbon dioxide equivalent (CO₂e) emissions from international voyages, and it changes the operating cost of global shipping lines [1]. Under Directive (EU) 2023/959, compliance is phased in at 40% of verified emissions in 2024, 70% in 2025, and 100% from 2026. The average secondary market allowance price recorded by the International Carbon Action Partnership was €65.23 per tonne of CO₂ in 2024 [2].

Seaport competitiveness is no longer set only by geography, channel depth, or berth throughput. A

port's competitiveness now depends on its capacity to supply certified zero-carbon marine fuel that meets the sustainability and mass-balance rules for CO₂ "zero-rating" under the EU ETS, which lowers the compliance cost of calling vessels [3, 4]. A guarantee of origin certificate converts a domestic power contract into a valid EU ETS offset [3]. The requirement creates a structural gap between Singapore, the region's leading hub, and CM-TV, the emerging gateway in Southern Vietnam.

Singapore holds a strong position through advanced port automation and multi-fuel bunkering, documented in its 2024 sustainability report [5]. However, Singapore is a densely populated city-state with a small domestic renewable energy base, and its dependency on imported green fuel sets a cost floor that a domestically endowed competitor can undercut.

CM-TV holds a different advantage rooted in geography. Vietnam has an estimated offshore wind

*Corresponding author. Email: chungntt@ut.edu.vn

technical potential of 1,068 GW in its exclusive economic zone, with 475 GW suitable for fixed-bottom foundations, and the best resources sit along the southern coast near CM-TV [6, 7]. Decree No. 57/2025/ND-CP establishes the direct power purchase agreement (DPPA) mechanism [8]. The decree permits terminal operators to purchase verified renewable electricity to decarbonize operations and supply shore power. Consequently, CM-TV secures domestic certified-origin proof, whereas Singapore relies on imported energy supplies [8, 9]. The two hubs each sit beyond the 300 nautical mile radius from any EU member state, so each is excluded from the Neighbouring Container Transshipment Port (NCTP) list and each resets extra-EU voyage emissions for calling vessels [10]. Hub competition depends on the supply of low-cost, zero-carbon marine fuel. It does not depend on routing rules. The study evaluates this asymmetry in energy origin, not engineering capability.

CM-TV and Singapore differ in cargo function. Vietnam's national port strategy assigns CM-TV a gateway role, projecting 75 to 80 percent import-export cargo and only 20 to 25 percent transshipment cargo by 2050 [11]. International transshipment ambition sits instead with Can Gio, a new port planned at the mouth of the same Cai Mep river estuary. In January 2025 the Prime Minister approved the investment policy for the Can Gio International Transshipment Port project, with a planned investment of at least VND 50 trillion over about 571 hectares at the estuary mouth [12]. This project has not reached construction and is not yet in operation, so this paper keeps its focus on CM-TV, the terminal currently handling cargo, and treats Can Gio as a related future development that draws on the same offshore wind endowment and DPPA framework described below. This paper studies the transshipment competition with Singapore as a contest centered on CM-TV, with the Can Gio project noted as part of Vietnam's longer-term port strategy for this estuary. A separate deep-water project, the proposed Hon Khoai seaport in Ca Mau, is positioned mainly for bulk and dual-use cargo, not container transshipment, and falls outside the scope of this comparison.

Earlier port competitiveness studies rely on static, linear methods that miss the non-linear feedback between energy policy, carbon regulation, and routing choices [13, 14]. A static comparison can rank two ports using fixed indicators, but it cannot capture how a cost advantage compounds through repeat calls or how a congestion bottleneck can erase that advantage a few years later. To the authors' knowledge, no published study has combined the TOE framework with Causal Loop Diagramming to compare a resource-rich emerging port against a resource-constrained incumbent hub under carbon pricing.

The study investigates the impact of Vietnam's renewable energy endowment and the DPPA mechanism on the competitive positioning of CM-TV versus Singapore under the expanded EU ETS. It (i) sets out the mechanics of the EU ETS and the NCTP clause, (ii) builds an evidence-based TOE readiness assessment of the two hubs, and (iii) uses Causal Loop Diagramming to model the feedback between energy endowments, carbon compliance cost, and liner routing. Section 2 reviews the relevant literature; Section 3 sets out the TOE assessment, the cost function, and the CLD structure; Section 4 reports the readiness matrix, the scenario trajectory, and the cost simulation; Section 5 discusses the asymmetry, its implications, and the limitations of the study; Section 6 concludes.

The paper makes two contributions. First, this study introduces resource-based competitive asymmetry in maritime carbon compliance. A physical renewable energy endowment creates a persistent, non-imitable advantage. The TOE framework evaluates the organizational readiness required to monetize this resource [15, 16]. Second, a four-loop CLD produces scenario-specific policy guidance that a static comparison cannot offer, tracing how a cost advantage in green bunker fuel can be reinforced or eroded by terminal congestion and certificate auditing capacity.

2. Literature Review

2.1. Carbon pricing and maritime compliance

A growing body of work treats market-based carbon measures as a force that reshapes the cost structure of shipping, beyond a simple compliance charge. The EU ETS adds a direct carbon liability to the voyage cost function of liner operators, set by the allowance price, the phase-in coefficient $\alpha(t)$, and the emission volumes across extra-EU, intra-EU, and at-berth voyage segments [1]. The liability scales with the allowance price set in the secondary market, so a shipping line's exposure changes with the same carbon market that steel and cement producers already face [2]. The FuelEU Maritime Regulation requires strict mass-balance proof and third-party guarantees of origin for a fuel to reach zero-rated status, so a port that can issue valid green certificates gives its calling fleet a direct financial advantage, as emission reductions must be validated by mass-balance certification, not unverified supplier declarations [4].

The NCTP clause establishes an asymmetric cost environment. Hubs on the NCTP list incur EU ETS liabilities on connecting voyages. By contrast, gateway ports outside this list provide a direct compliance cost reduction [10]. Singapore and CM-TV sit outside the 300 nautical mile radius that defines this list, so the clause treats them the same way. The competitive dynamic analyzed in this study operates inherently within this uniform regulatory framework. Given that

each hub resets extra-EU emissions in the same way, the determining variable is which hub offers a lower cost to the shipping line. The NCTP mechanism was built to prevent evasive port calls, not to confer a competitive edge, so its symmetry here is expected, not incidental: case-study evidence on EU-adjacent transshipment hubs shows that switching to a nearby non-EU alternative only becomes cost-effective at carbon prices well below €25 per tonne [17], far under the EUA levels used in this study. This supports treating fuel economics, not NCTP positioning, as the mechanism under test.

2.2. Port competitiveness and the energy endowment gap

Port selection research is moving away from pure operational metrics toward decarbonization capacity. Singapore has invested in alternative fuel bunkering at Tuas Port, including liquefied natural gas and green methanol operations [5], on top of a strong existing base in automation, digital compliance tracking, and network connectivity that keeps it attractive to shipping alliances in the near term. Yet this import-dependent fuel structure leaves the city-state open to external market shocks: local wind speeds average in the 2 to 3 m/s range, unsuitable for wind power, so almost all decarbonization pathways run through imported electricity or fuel [9, 18].

Recent techno-economic work shows that Vietnam can reach a Levelized Cost of Hydrogen (LCOH) of 1.24 to 1.65 USD/kg, low enough to undercut a hub that must import alternative fuel at international prices [19]. Developing-country ports face two main barriers: weak institutional capacity and limited access to green finance [20]. These factors prevent ports from converting renewable energy endowments into competitive advantages. These barriers set the research scope: evaluating CM-TV's capacity to develop the requisite institutional framework to leverage existing resources before Singapore closes the fuel-cost gap through imported supply.

Part of that institutional layer is emerging through bilateral green shipping corridors, agreements that commit a load centre and a gateway port to a joint decarbonization timeline. Reviews of maritime decarbonization policy treat these corridors as an instrument that can align a port's domestic energy investment with a shipping line's decarbonization targets, since a corridor agreement gives a project financier a demand signal it would not otherwise have [20]. Section 5.3 returns to this as one of the policy priorities that follow from the CLD results.

2.3. Resource-based competitive asymmetry

The Resource-Based View (RBV) frames this asymmetry [15, 16]. Singapore's long-standing competitive edge

came from its information technology and operational capability, which offset its limited natural resource base [21]. Under carbon pricing, this balance shifts. Vietnam's offshore wind potential works as a Valuable, Rare, Inimitable, and Organized (VRIO) resource [16]. Singapore's technology base stays valuable, but it can be replicated with capital and it remains energy-import dependent [9]. Vietnam's renewable endowment sits in its physical geography and cannot be copied the same way, as geographical factors constrain Singapore's domestic offshore wind potential, irrespective of capital investment. The classification follows deductively from applying the VRIO criteria to the evidence in Table 1; Section 5.4 returns to this as a theory-driven categorization, not an independently tested measurement.

Classical trade theory already explains why a wind-rich country exports wind-based energy: factor-endowment theory predicts comparative advantage from a country's relative supply of land, labor, and capital. That theory operates at the level of nations trading goods, and it does not explain why one port operator converts a national energy endowment into a certified, bankable fuel supply while another with access to the same national grid does not. The VRIO layer added here sits at the level of the port organization, not the nation: it evaluates whether CM-TV's management, certification systems, and finance access let it turn the wind endowment into a compliance-grade fuel product before a competitor closes the gap. RBV and factor-endowment theory answer different questions, one at the country level and one at the organizational level. The endowment sets the ceiling on what CM-TV can supply, while the TOE-assessed organizational capacity in Table 3 sets how much of that ceiling it can reach.

The realization of this advantage depends on operational capacities. Liner networks show high path dependency and heavy switching costs, so shipping alliances are unlikely to leave an incumbent hub outright and are more likely to add a resource-rich gateway as a compliance stopover [22]. Converting raw renewable electricity into marine bunker fuel also needs a Power-to-X (PtX) supply chain, and this needs capital and years to build [19, 23]. The study integrates the TOE framework with the RBV. Vietnam's wind potential is the primary resource. Subsequently, the TOE assessment evaluates CM-TV's organizational and technological readiness for commercialization [13].

2.4. Systems Thinking and the TOE framework

Traditional linear models are computationally inadequate for capturing the dynamics of maritime logistics systems, where a policy shock such as carbon pricing produces non-linear, time-delayed, and cascading effects

[14], consistent with the general case for Systems Thinking in complex, feedback-driven systems [24]. A cost table can show the price gap between two ports on the day it is built, but it cannot show how that gap changes once shipping lines respond to it, congestion builds up, or certification capacity catches up with new supply. System Dynamics modelling of deep-sea ports shows how investment cycles, throughput growth, and environmental compliance interact through feedback [25], and Causal Loop Diagramming of shore power shows it can reduce carbon leakage through a reinforcing loop that a linear model cannot see [26]. The resulting CLD maps reinforcing loops, balancing loops, and time-delayed causal links between policy and market response.

The TOE framework, first built for technology adoption and later applied to green logistics innovation [13], defines its Environment dimension as the industry structure, competitors, and regulatory environment facing the firm. This study extends that dimension to include the physical renewable energy endowment available to the port, on the reasoning that a resource endowment, like the regulatory environment, is exogenous to the port operator and bounds what organizational investment alone can achieve; this is an adaptation of the original construct, not a direct application of it. With that extension, the framework fits a comparative port decarbonization assessment: it captures infrastructure readiness, governance capacity, and environmental resource endowment in one combined assessment. Combining TOE with Systems Thinking to assess port competitiveness under carbon pricing is the methodological contribution of this paper; a systematic review protocol was not run to confirm this gap, a scoping limit Section 5.4 notes.

3. Methodology

The study combines document analysis, a TOE readiness assessment, and Causal Loop Diagramming. The qualitative structure is checked against a deterministic cost-accounting simulation, so the feedback mechanisms in the CLD stay grounded in the financial reality of maritime carbon pricing [1].

3.1. TOE readiness assessment

The Technology dimension covers alternative fuel bunkering, shore power, and digital compliance systems. Evidence for Singapore comes from its audited sustainability report [5], and evidence for CM-TV comes from terminal equipment assessments [27]. The Organization dimension covers sustainability governance, verified greenhouse gas inventory capacity, and access to green finance. CM-TV's organizational readiness rests on its ISO 14064-1 greenhouse gas inventory, verified by the British Standards Institution [28], and Vietnam's developing carbon market framework

[29]. The Environment dimension covers the renewable energy endowment and the regulatory framework that supports it. Evidence for Vietnam's offshore wind potential comes from national meteorological assessment [6, 7], and the DPPA mechanism rests on Decree No. 57/2025/ND-CP [8].

To ensure methodological rigor and mitigate subjective bias, Table 1 details the indicator used for each dimension and the source that supports it. Each indicator is supported by official documentation, regulatory instruments, or empirical reports.

Each indicator is scored using a four-level rubric: Nascent (a target or feasibility study exists, with no legal framework or capital committed), Emerging (an early regulatory framework or pilot project is verified), Mature (large-scale commercial operation with international verification), and Transformative (a physical resource with no feasible domestic substitute at the competing hub, backed by an enacted legal framework for its commercial use). A fifth qualifier, Structurally Constrained, applies only to the Environment dimension, for a case where geography, not policy or capital, sets the limit. Appendix A gives the full wording of each rubric level. Each rating in Table 3 was assigned by the research team from the sources in Table 1; a second, independent coder did not cross-check these ratings, and Section 5.4 flags this as a methodological limitation. Table 3 reports one rating per dimension, built from the indicators in Table 1. A dimension-level rating is assigned only when its component indicators converge on the same qualitative level, as they do for Singapore and CM-TV across all three Environment indicators here. A dimension with indicators split across levels would need a separate, stated tie-breaking rule not used in this study.

3.2. Carbon compliance cost function

Adapting recent maritime cost-accounting work [1] to the parameters set by Directive (EU) 2023/959, the total generalized cost for a vessel calling at a transshipment hub is:

$$GC_{port} = C_{voyage} + C_{port} + C_{switching} + C_{bunker} + [P_{EUA} \cdot \alpha(t) \cdot (E_{extra} + E_{intra} + E_{berth})] - S_{zero} \quad (1)$$

where C_{voyage} and C_{port} are standard voyage and handling costs (with C_{voyage} reduced by the fossil fuel displaced by alternative fuel use); $C_{switching}$ is the network cost of rerouting to a new compliance stopover; P_{EUA} is the European Union Allowance price, €65.23/tonne on average in 2024 [2]; $\alpha(t)$ is the phase-in factor, 0.40 in 2024, 0.70 in 2025, and 1.00 from 2026; E_{extra} , E_{intra} , and E_{berth} are the baseline CO₂e

Table 1. Operationalization of the TOE framework for evidence-based assessment

Dimension	Indicator	Evidence source
Technology	Alternative fuel bunkering infrastructure	PSA sustainability disclosure [5]
Technology	Shore power and cold ironing capacity	Terminal equipment assessment [27]
Technology	Digital compliance and GHG monitoring	PSA sustainability disclosure [5]
Organization	Sustainability governance maturity	PSA disclosure; Gemadept disclosure [5, 28]
Organization	Verified GHG inventory capacity (ISO 14064-1)	Gemadept Sustainability Report [28]
Organization	Access to green finance and carbon markets	Developing-country decarbonization review [20]
Environment	Domestic renewable energy endowment	Offshore wind policy study; national technical assessment [6, 7]
Environment	National regulatory framework for DPPA	Decree No. 57/2025/ND-CP [8]
Environment	Carbon cost resilience	Vietnam ETS review; Singapore grid study [9, 29]

emissions on extra-EU voyages (50% scope), intra-EU voyages (100% scope), and at berth in the EU (100% scope); S_{zero} is the cost saving from certified zero-carbon fuel or renewable shore power that meets FuelEU mass-balance rules; and C_{bunker} is the cost of the zero-carbon fuel a vessel must buy to meet FuelEU greenhouse gas intensity limits.

Equation (1) combines two separate EU instruments, and keeping them distinct matters for how S_{zero} and C_{bunker} are read. The EU ETS, through the MRV Regulation (EU) 2015/757 as amended, allows a zero emission factor for certified sustainable fuels, extended to renewable fuels of non-biological origin by Delegated Regulation (EU) 2024/3214 with effect from 1 January 2024 [30]; this is the mechanism S_{zero} represents, and it is a provision of the EU ETS itself, not an offset bought from outside the scheme. FuelEU Maritime [4] is a separate instrument, with its own greenhouse gas intensity target, penalty, and banking and pooling mechanism; it is what forces the fuel purchase represented by C_{bunker} . Both the EU ETS at-berth scope and FuelEU's onshore-power credit apply only inside the EU, so DPPA-sourced shore power consumed at CM-TV, outside the EU, qualifies for neither directly. Its effect in this model is indirect: lower auxiliary fuel consumption while the vessel is in port, which reduces the total voyage fuel burn and so E_{extra} .

Singapore and CM-TV sit outside the 300 nautical mile NCTP radius, so calling at either port resets the extra-EU emissions calculation [10]. Routing to CM-TV needs a southbound detour past Singapore, which raises voyage emissions and C_{voyage} . Vietnam's offshore wind potential supports domestic Power-to-X fuel production, which can lower C_{bunker} [6, 8]. Singapore's space and resource limits require imported green fuel, which sets a

price premium on C_{bunker} that a domestic Vietnamese producer can undercut [19].

A deterministic simulation illustrates the sensitivity and interactions of the variables defined in Equation (1). Holding C_{voyage} , C_{port} , and $C_{switching}$ fixed, the term that changes most between the two hubs is C_{bunker} , set by where the green fuel is produced, not by where the vessel calls. Section 4.3 populates this term with published cost data and shows that the fall in C_{bunker} at CM-TV outweighs the rise in C_{voyage} from the longer routing distance.

3.3. Causal Loop Diagramming

Formal System Dynamics needs a quantitative stock-and-flow simulation, and the pricing history for domestic Power-to-X fuel in Vietnam is still short, so this study uses qualitative Causal Loop Diagramming instead, built from peer-reviewed literature, corporate disclosure, and state policy documents [14, 25, 26].

The CLD in Figure 1 maps four mechanisms.

R1 (Resource endowment, reinforcing): Activated via the DPPA, Vietnam's offshore wind potential enables CM-TV to supply verified renewable electricity and zero-carbon fuel. A reduction in C_{bunker} decreases GC_{port} , thereby attracting higher call volumes and scaling renewable procurement. The loop carries a long time delay, since an offshore wind project needs about seven years from site assessment to commercial operation [6], and in the near term runs mainly through DPPA-enabled shore power, not full Power-to-X synthesis; grid capacity limits and Power-to-X lead time also slow it.

R2 (Governance and technology, reinforcing): Singapore's governance maturity and technology base support shipping line confidence [5], reinforced by sovereign

capital that can secure imported green fuel corridors at a scale CM-TV cannot yet match, though CM-TV is closing this gap through its ISO 14064-1 certification and Vietnam's developing carbon market [28, 29].

B1 (Infrastructural friction, balancing): A surge in calls at CM-TV raises pressure on terminal capacity, and equipment inefficiency there is already linked to congestion and delay [27], raising GC_{port} and offsetting the gain from R1.

B2 (Institutional verification, balancing): The saving from green energy only counts once electricity is verified through a recognized mass-balance and guarantee-of-origin certificate; a gap in auditing capacity can delay this and keep GC_{port} high even where renewable supply exists [20].

This table lists the links shown in Figure 1 so the loop structure can be checked independently of the figure itself; notation in the figure should be read as matching Equation (1) (S_{zero} , E_{extra} , E_{intra} , E_{berth}).

3.4. Data sources and triangulation

The document analysis behind Table 1 and the CLD in Figure 1 draws on three kinds of source, checked against one another: peer-reviewed studies for theoretical grounding and independent measurements, such as offshore wind resource assessments and terminal equipment audits [6, 7, 27]; corporate disclosures, such as the PSA and Gemadept sustainability reports, for operational and governance evidence [5, 28]; and state policy documents, such as Decree No. 57/2025/ND-CP and the EU directives cited in Section 3.2, for the legal parameters that fix the boundaries of Equation (1) [3, 4, 8, 10]. All three source types are documentary; no interview or workshop with shipping line routing managers or port operators cross-checked the causal links or the ratings in Table 3, a limit Section 5.4 returns to.

4. Results

4.1. Readiness assessment

Table 3 sets out a comparative readiness assessment. Singapore reaches Mature status in Technology and Organization, but its Environment rating is Structurally Constrained: it is a space-constrained city-state with wind speeds in the 2 to 3 m/s range, unsuitable for wind power, and it depends on imported electricity and fuel [9, 18]. CM-TV is Nascent to Emerging in Technology and Organization, but Transformative in Environment, on the strength of its 475 GW offshore wind potential and the Decree No. 57/2025/ND-CP DPPA framework [6–8]. This Transformative rating reflects the scale of the resource and the legal framework enabling its use, not an operating project: as of this writing, no offshore wind project in Vietnam has reached a final investment decision [31].

The pattern points to a resource-based asymmetry that cutting across technology or organization cannot close: Singapore's technology and governance lead is real, but its Environment rating stays fixed unless its physical geography changes, while CM-TV's Technology and Organization gaps are the kind that investment and training can close over time [20].

A Mature rating in Technology and Organization took Singapore several decades to reach [5, 21]; CM-TV's Nascent to Emerging rating on the same two dimensions reflects a cluster still early in that process, though a shorter path is open to it, since it can adopt already-proven digital compliance systems and shore power designs. It does not need to develop these systems from the start. The Environment dimension offers Singapore no such shortcut, since no management practice can substitute for a domestic renewable resource that does not exist.

4.2. Scenario trajectory

The CLD structure implies a four-stage trajectory as EU ETS enforcement tightens and Vietnam's energy policy matures.

Scenario 1, baseline equilibrium (before 2024). Singapore holds its position on operational efficiency, automation, and technology [5], and CM-TV serves mainly as a secondary hinterland gateway. Green fuel cost plays almost no part in routing choice, since no carbon liability yet attaches to the voyage.

Scenario 2, carbon cost shock (2024 to 2025, $\alpha(t)$ of 0.40 to 0.70). Shipping lines begin to weigh C_{bunker} in their routing choice as the EU ETS phases in, and Singapore's import-dependent fuel strategy starts to strain against this new cost variable [1, 9]. The competitive question shifts to which hub can offer the fleet a lower blended-fuel cost.

Scenario 3, green hub transition (2026 to 2028, $\alpha(t)$ at 1.00). At full enforcement, DPPA activation lets CM-TV supply verified renewable electricity and, once behind-the-meter Power-to-X capacity is in place, certified e-methanol that satisfies both the EU ETS zero-rating criteria and FuelEU's guarantee-of-origin rules, activating loop R1 in its entirety [4, 8]. In the near term, before that capacity exists, DPPA-sourced grid electricity supports shore power that reduces the vessel's auxiliary fuel burn at CM-TV. It does not qualify for EU-port-specific zero-rating. The cost simulation in Section 4.3 models the fuel-synthesis case directly, since it assumes DPPA-enabled Power-to-X supply and certificate verification each work as designed.

Scenario 4, infrastructure and verification lag (2025 to 2030). Vietnam's national power plan sets a near-term offshore wind target far below the 475 GW technical ceiling [6], so a premature volume surge can let B1 (congestion) and B2 (verification delay) erode the gain

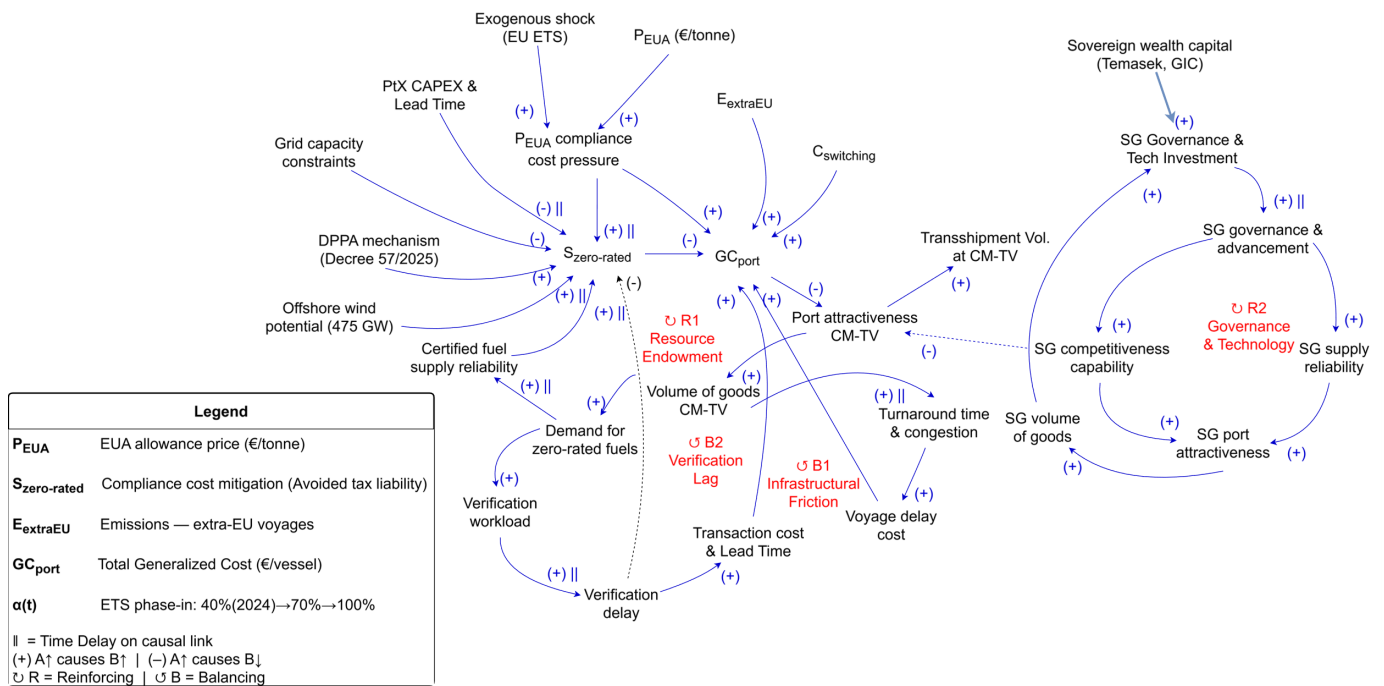


Figure 1. Causal Loop Diagram of green port competitiveness between CM-TV and Singapore

Table 2. Causal link summary for Figure 1

Link	Polarity	Evidence source	Approximate delay
DPPA mechanism to renewable electricity and shore power supply	+	[8]	Short
Renewable electricity supply to C_{bunker}	-	[7, 19]	Long for Power-to-X fuel; short for shore power
C_{bunker} to GC_{port}	+	Equation (1)	None
GC_{port} to call volume at CM-TV	-	[22]	Medium
Call volume to renewable procurement scale	+	[12]	Medium
Offshore wind site assessment to commercial operation (gates R1)	gating	[6]	Long, about seven years
Singapore governance and technology base to shipping line confidence	+	[5]	Short
CM-TV ISO 14064-1 certification to organizational competitiveness	+	[28, 29]	Medium
Call volume at CM-TV to terminal congestion	+	[27]	Short
Terminal congestion to GC_{port}	+	[27]	Short
Offshore wind deployment pace relative to certification capacity	gating	[20]	Medium
Certification capacity gap to realized S_{zero}	-	[20]	Medium

before capacity and certification catch up [20, 27]. CM-TV's advantage here rests mainly on DPPA-enabled shore power, not full Power-to-X synthesis, since offshore

wind construction and fuel plant build-out each run on multi-year timelines.

Scenarios 3 and 4 describe the same 2026 to 2030 window under two different assumptions, not two

Table 3. Comparative readiness assessment

Dimension	Key indicators and evidence	Singapore	CM-TV
Technology	Alternative fuel bunkering, shore power, digital compliance monitoring [5, 27]	Mature	Nascent
Organization	Sustainability governance, verified GHG inventory, access to green finance [5, 20, 28]	Mature	Emerging
Environment	Renewable energy endowment, DPPA/REC regulatory framework, carbon cost resilience [6–9, 29]	Structurally con- strained	Transformative

sequential periods: Scenario 3 traces the trajectory if DPPA supply and certification capacity keep pace with demand, and Scenario 4 traces it if they do not. Which trajectory dominates in practice depends on the relative pace of loop R1 against loops B1 and B2. Together, these four stages show that CM-TV's advantage does not appear the day the DPPA decree is signed. It builds gradually over Scenarios 2 and 3, and Scenario 4 sets the boundary condition for how much of it survives into a stable routing pattern.

4.3. Cost simulation

A deterministic simulation for a 20,000 TEU vessel on an Asia-North Europe route tests the CLD model; the FuelEU blending mandate, not tax avoidance, drives fuel choice [4]. The simulation holds the phase-in factor $\alpha(t)$ at 1.00 throughout, matching the fully enforced Scenario 3 window in Section 4.2. The two EUA prices used below, the 2024 average of €65.23 per tonne and a €90.00 per tonne benchmark, are applied under this full-enforcement assumption. They do not represent a saving realized in a past year: in 2024 $\alpha(t)$ stood at 0.40, and CM-TV's domestic e-methanol supply chain had not yet reached construction, as Section 5.4 notes.

The saving reported below is a FuelEU-driven green-fuel-cost result, not an EU ETS result: on the ETS component alone, CM-TV is worse off than Singapore by €30,482 per leg before adjustment, since the longer detour raises baseline voyage emissions. The net advantage comes entirely from the lower cost of e-methanol produced domestically, which FuelEU's blending mandate requires both hubs to procure. This simulation also represents a single-string substitution: a vessel calls at CM-TV, not Singapore, as its last port of call. This is not an added stop alongside Singapore; a dual-hub rotation that calls at both ports, as discussed in Section 5.2, would carry its own network switching cost ($C_{switching}$ in Equation 1), which is not modeled here. The 10% blend share used below is also an above-minimum case: FuelEU's own well-to-wake intensity reduction target is 2% for 2025 to 2029 and 6% from 2030, so 10% is an illustrative, commercially ambitious scenario, not the compliance floor. The net saving below

scales roughly in proportion to the blend share chosen. The 10% share is set on an energy basis, not a mass basis; e-methanol carries a lower energy density than conventional bunker fuel, which is why the mass-based e-methanol tonnage needed, about 690 to 750 tonnes below, runs close to double the nominal 10% share of total fuel mass.

Routing through Singapore, a voyage to Rotterdam runs about 23 days and 3,450 tonnes of fuel oil equivalent, for 10,743 tonnes of CO₂ and a baseline ETS liability near €350,330 at the 50% extra-EU scope. Meeting a 10% green fuel blend needs about 690 tonnes of e-methanol, and Singapore's import-parity price of about €1,400 per tonne [32] sets C_{bunker} near €966,000.

Routing through CM-TV adds a two-day southbound detour, for 25 days and 3,750 tonnes of fuel oil equivalent, 11,677 tonnes of CO₂, and a baseline ETS liability near €380,812, a raw detour penalty of €30,482 before adjustment for S_{zero} , plus a raw extra fuel cost of about €135,000 (300 tonnes of additional heavy fuel oil at roughly €450 per tonne, broadly consistent with conventional bunker fuel price levels reported by industry indices in 2024 to 2025). The 10% green fuel blend needs about 750 tonnes of e-methanol. CM-TV's domestic production cost is set at about €800 per tonne, a planning figure consistent with Vietnam's reported levelized cost of hydrogen of 1.24 to 1.65 USD/kg [19] and with published e-methanol cost estimates of €600 to €680 per tonne at the best renewable sites by 2030 [33]. The step from the hydrogen cost to this methanol figure, including the hydrogen input per tonne of methanol, the CO₂ feedstock cost, and plant capital charges, is not shown in this short version; the €800 per tonne figure should be read as an illustrative planning assumption, not a value reported directly in either cited source. This sets C_{bunker} near €600,000.

Table 4 sets out the full calculation. The gross saving from domestic fuel at CM-TV over Singapore is the difference between the two C_{bunker} figures, about €366,000. Before this gross saving can be compared with the cost of the longer CM-TV routing, the two raw detour costs need one more adjustment for S_{zero} : since the 10% green fuel blend also displaces 10% of the conventional

Table 4. Net saving computation per leg at the 2024 EUA price (€65.23/tonne)

Cost item	Amount (€)
Singapore C_{bunker} (690 t e-methanol at €1,400/t)	966,000
CM-TV C_{bunker} (750 t e-methanol at €800/t)	600,000
Gross bunker saving	366,000
Less: ETS liability from detour, adjusted for S_{zero}	-27,434
Less: conventional fuel cost from detour, adjusted for S_{zero}	-121,500
Net saving per leg	217,066

fuel volume on each leg, the raw detour penalty of €30,482 and the raw extra fuel cost of €135,000 each fall by 10%, to €27,434 and €121,500. This gross saving must absorb these two adjusted costs from the longer CM-TV routing. The net saving is about €217,000 per leg, or roughly €11.3 million a year on a weekly service loop at the 2024 EUA price; these are rounded, illustrative figures under the stated assumptions, not precise forecasts. Table 5 illustrates this pattern at two EUA price points, using the same line items at each price; the direction holds across the range of Equation (1), since a higher P_{EUA} raises the compliance liability for each hub but by more for the longer CM-TV routing, narrowing the net saving as the EUA price rises. This two-point table is an illustration, not a continuous sensitivity sweep, and the saving itself is an illustrative point estimate under the stated assumptions, not a forecast: it depends on CM-TV's domestic e-methanol production reaching the €800 per tonne cost used here, a production scale that Section 5.4 notes is not yet operating.

The two adjusted rows equal the raw detour costs (€30,482 and €135,000) reduced by 10%, the share of voyage energy met by the FuelEU-compliant green fuel blend. This reduction is the S_{zero} term in Equation (1): it lowers each hub's own EU ETS liability and displaced-fuel cost by the share the green blend covers, before the CM-TV detour penalty is computed. C_{bunker} in Equation (1) corresponds to the two production-cost rows above; the two adjusted rows correspond to the change in E_{extra} and C_{voyage} from the longer CM-TV route.

The saving scales beyond a single vessel: an alliance running several weekly loops would multiply the saving across every vessel it commits to a CM-TV rotation, compounding further once call volume unlocks the scale economies in loop R1. A rising EUA price narrows the margin, since it raises the liability CM-TV must absorb for its longer routing faster than it raises the liability the

Table 5. Sensitivity of annual saving per weekly service loop to EUA price

EUA price	Net saving per leg	Annual saving
€65.23 [2]	€217,066	€11.29 million
€90.00 [1]	€206,652	€10.75 million

Table 6. Sensitivity of net saving per leg to the e-methanol price gap (at €65.23/tonne EUA)

Price gap, Singapore minus CM-TV (€/tonne)	Net saving per leg
€400	€67,066
€600 (base case)	€217,066
€800	€367,066

fuel blend offsets, so Vietnam's window to convert this into a durable share of transshipment volume sits widest while the EUA price stays near its current level.

The simulation uses e-methanol as the reference fuel, the pathway most reviews treat as the leading option for deep-sea shipping [23]. The same domestic cost advantage should extend to other Power-to-X products such as green ammonia, since the offshore wind endowment that supports hydrogen production carries over directly; ammonia synthesis needs green hydrogen and nitrogen, not a carbon feedstock.

The EUA price is not the variable the result is most sensitive to. The table below holds the EUA price at €65.23 and varies the e-methanol price gap between Singapore and CM-TV instead: each €200 per tonne change in the gap moves the net saving per leg by about €150,000 (the 750 tonne CM-TV blend volume times the price change), an order of magnitude larger than the roughly €10,400 per leg spread across the full €65.23 to €90.00 EUA range above.

4.4. Synthesis of results

The convergence of the TOE assessment, CLD trajectory, and cost simulation indicates that CM-TV's cost advantage is real but conditional. The readiness matrix explains why CM-TV can compete on cost, given its Transformative rating on Environment; the scenario trajectory explains when this advantage becomes available, marking Scenario 3 as the period when DPPA supply and FuelEU certification each become active; and the cost simulation gives it an illustrative number, roughly €11.3 million a year on a single weekly service loop at the 2024 EUA price. Vietnam's offshore wind endowment and the DPPA

mechanism reshape CM-TV's attractiveness by giving it a cost lever that Singapore cannot pull at home, though this lever only becomes usable once the conditions in Scenario 3 are met.

5. Discussion and Policy Implications

5.1. Resource-based competitive asymmetry

The TOE and CLD results together point to a resource-based competitive asymmetry that a standard port benchmark cannot capture. CM-TV's advantage does not come from capital spending alone, but from a physical offshore wind endowment that a land-scarce city-state does not have access to [6, 7]. Singapore's import dependency sets a persistent cost floor for green fuel [9]: it can keep investing in technology and governance, but this cannot change its Environment rating, while CM-TV's governance and technology gaps are open to closing through targeted investment [20].

A reasonable objection asks why calling vessels must divert to CM-TV when Vietnamese green methanol could be imported directly to Singapore, since methanol is a liquid chemical commodity that tankers already carry across borders. Maersk has bunkered green methanol sourced from Chinese production at its Shanghai call [34], and Singapore is opening its own methanol bunkering licences from 2026 [35], so a Vietnam-to-Singapore supply chain is not implausible. This objection has real force, and the position taken here rests on a practical basis, not a legal one. The additionality, temporal and geographic correlation rules for renewable fuels of non-biological origin under Delegated Regulation (EU) 2023/1184 [36] govern how the electricity used to produce the fuel is sourced; they do not tie a certified batch to a particular bunkering location, so a verified Vietnamese e-methanol cargo could in principle retain its RFNBO status at a Singapore terminal, much as biofuels already move internationally under mass-balance bookkeeping. What does not yet exist is the verified import and mass-balance infrastructure on the Singapore side for Vietnamese e-methanol specifically, together with the shipping and storage chain to carry it there. CM-TV's near-term position rests on being the first point where production and bunkering are co-located under the DPPA mechanism, not on a regulatory bar against importing the fuel elsewhere. Short-sea chemical tanker freight between CM-TV and Singapore is typically a small fraction of the €600 per tonne production cost gap, though the authors have not obtained a verified freight quote for this specific route and do not state a figure here.

The asymmetry also explains why the two hubs are unlikely to converge over time. A gap built from capital and management practice narrows whenever the lagging side invests, since capital can move to wherever the

investment goes. Geographical and climatic constraints, by contrast, represent durable structural barriers to domestic renewable energy parity, and this barrier holds even as Singapore diversifies its cross-border electricity imports, since the resource still originates outside its own territory [9].

5.2. Managerial implications for shipping alliances

Liner alliances have a clear cost incentive to optimize port call sequencing. Full displacement of Singapore is not the likely outcome, once the cost advantage in Table 5 becomes available at scale. Path dependency and switching cost in liner networks rule out a full displacement of Singapore [22]; a more likely outcome is a dual-hub strategy, where alliances keep Singapore for mega-consolidation and add CM-TV as the last port of call on direct Asia-Europe loops, resetting extra-EU emissions and bunkering lower-cost compliance fuel before heading to Europe. The routing strategy is primarily governed by fuel economics, given that the NCTP reset applies uniformly to both hubs [10]. Early strategic commitment enables alliances to secure priority access to DPPA-enabled capacity and establish fixed-price bunkering agreements before local production costs rise with demand. Delayed integration into Scenario 4 decreases cost savings due to congestion and certificate queues, which compress the advantage once volume grows quickly.

5.3. Policy implications

Four priorities follow from the balancing loops and the pace of the scenario trajectory in Section 4.2.

First, bridging the certification gap (B2) requires Vietnam to build a national Energy Attribute Certificate registry meeting FuelEU mass-balance rules and train certified auditors, building on the template set by Gemadept's ISO 14064-1 verification [4, 28]. This registry is essential: absent it, the projected cost advantage in Table 5 remains invalid for compliance offsets.

Second, bridging the infrastructure gap (B1) requires a regional capacity coordination mechanism across the former Ba Ria-Vung Tau area, now part of Ho Chi Minh City following the 2025 provincial merger, covering berth allocation and shared investment. The mechanism can stop congestion from eroding the cost advantage, using terminal equipment data to set upgrade priorities [27]. It matters most in Scenario 4, when call volume can rise faster than berth capacity.

Third, accelerating the resource loop (R1) requires a green economic zone at CM-TV, with incentives for offshore wind developers and Power-to-X producers. The zone must establish direct, behind-the-meter links

between wind generation and fuel synthesis, ensuring compliance with EU rules on renewable fuel of non-biological origin, which require a real additionality link that a grid-connected DPPA contract alone does not meet [36]. Bilateral green shipping corridors with load centres such as Rotterdam and Hamburg can de-risk the capital needed for this infrastructure and give a long-term offtake signal that turns a feasibility study into a financed project [20].

Fourth, planning the physical build-out requires retrofitting deep-water berths with high-voltage shore connection systems, cabling, substations, and safe buffer storage for alternative fuel such as liquid ammonia or methanol [27]. The build-out must be phased so it does not stop container handling during the 2025 to 2030 window identified in Scenario 4.

5.4. Limitations and future research

The cost function in Equation (1) is set by Directive (EU) 2023/959 and Implementing Regulation (EU) 2023/2297 as they stood when this paper was written, and these boundary conditions can shift again before the window described in Scenario 3 closes. The study also rests on a qualitative CLD, not a quantitative stock-and-flow simulation, since long-run pricing data for Vietnamese Power-to-X fuel are still limited; a qualitative model shows the direction and rough timing of each loop but not the exact point where a balancing loop overtakes a reinforcing one. All evidence behind Table 1, Table 3, and Figure 1 is secondary and documentary, with no interview or workshop with routing managers or port operators to validate the causal links or to check the ratings against a second, independent coder. Expert elicitation and an inter-rater reliability check would strengthen confidence in these results before they inform policy design. The claim in Section 2.4 that this paper is the first to combine the TOE framework with Causal Loop Diagramming for port decarbonization rests on a standard literature search, not a formal systematic review protocol with a registered search string and dual screening. A comparable prior study cannot be ruled out with full certainty on this basis.

The cost simulation uses deterministic price assumptions for the EUA price and the cost of e-methanol, each open to market and geopolitical shocks a single-point estimate cannot capture. CM-TV's domestic cost figures are incurred in Vietnamese dong and converted to euro for comparability, and exchange rate movement, not modelled here, adds a further source of uncertainty to the saving in Section 4.3. Liner routing also carries path dependency a pure cost-minimization model does not fully capture: existing terminal contracts and deployment plans can keep a route fixed for years after a cost advantage appears elsewhere [22]. Section 5.1 flags a further boundary condition: if a verified trade

route for Vietnamese green e-methanol into Singapore's own bunkering terminals matures, part of the fuel-cost advantage modelled here could transfer to Singapore even though vessel routing stays the same.

The cost simulation also omits the charter or capital opportunity cost of the two extra sailing days the CM-TV detour adds. This cost depends on the vessel's charter rate, which for a 20,000 TEU ship varies widely with freight market conditions and was not available from a verified source at the time of writing. As a rough check on scale, reported time-charter rates for large containerships in 2025 to 2026 ran from the mid tens of thousands of US dollars per day for mid-sized tonnage up to the order of a hundred thousand dollars per day for the largest, newest vessels; even the lower end of that range, applied to two extra days, is large enough relative to the €217,000 per-leg saving in Table 4 that this omission is a material limitation, not a cosmetic one. The authors did not verify a figure precise enough for the 20,000 TEU segment specifically to include here; a future version of this simulation should add a verified time-charter or capital cost line once available.

The scenario trajectory in Section 4.2 also assumes DPPA-enabled renewable supply activates within the Scenario 3 window (2026 to 2028). As of mid-2026, Vietnam's offshore wind sector remains at a preparatory, pre-construction stage: Decree No. 272/2026/ND-CP, effective from July 2026, sets out development-phase procedures for offshore wind projects, and no project has yet reached a final investment decision [31]. The seven-year site-to-operation timeline cited in Section 3.3 means full Power-to-X activation could fall later than Scenario 3 assumes, and the near-term saving in Section 4.3 should be read as resting on DPPA-enabled grid electricity and shore power, not on offshore wind fuel production that has yet to reach construction.

The comparison here is limited to Singapore and CM-TV. Other regional gateways, including ports in Malaysia and Thailand and other Vietnamese ports such as Hai Phong, face a similar carbon-pricing shock and may pursue a comparable strategy; the asymmetry described here is specific to this dyad, not a claim that CM-TV holds it over every competing hub in the region. As a two-case comparison, the study establishes a plausible mechanism, not a population-level finding, and needs testing against a larger set of ports before its external validity can be claimed.

Future work should move to quantitative System Dynamics once multi-year pricing and routing data are available, test the balancing loops identified here, congestion and certification lag, through discrete choice experiments with routing managers, and examine the sequencing between offshore wind construction and Power-to-X plant construction to date the shift from Scenario 4 to Scenario 3.

6. Conclusion

The paper traces the shift in competitive position between Singapore and CM-TV under the EU ETS, combining the TOE framework with Causal Loop Diagramming to show feedback structures that a standard port comparison cannot reveal.

The central finding is a resource-based competitive asymmetry: Singapore leads in technology and organizational readiness, but CM-TV's 475 GW offshore wind endowment, activated through Decree No. 57/2025/ND-CP, gives it an Environment advantage that Singapore has not been able to replicate domestically, converting into a lower compliance cost through S_{zero} . This advantage operates through FuelEU Maritime's fuel-cost channel, not through the EU ETS. CM-TV's longer routing is at a disadvantage on the ETS component alone, before the fuel blend is counted. The illustrative cost simulation in Section 4.3 puts this saving at roughly €11.3 million to €10.7 million a year per weekly service loop across the EUA price range tested, falling as the carbon price rises, though this figure depends on domestic fuel production reaching commercial scale and omits the vessel-time cost discussed in Section 5.4.

Two balancing loops, port congestion and certification capacity, can erode CM-TV's gain unless Vietnam builds the institutional and physical capacity to match its resource endowment, and the limitations in Section 5.4, most notably the reliance on secondary evidence and the two-case scope, mean this finding is a plausible mechanism to test further, not a settled result.

The port-energy integration model proposed here, anchored by a green economic zone, behind-the-meter links between wind generation and fuel synthesis, and bilateral green shipping corridors, sets out one path to hold this window open for CM-TV. Theoretically, this study contributes a dynamic evaluation framework combining TOE and CLD. Practically, it outlines a policy roadmap where the certification registry, the terminal capacity plan, and the green economic zone form three parts of one mechanism; the absence of any one part will constrain the integration of Vietnam's renewable capacity into maritime compliance workflows.

Author contributions

Nguyen Thi Thu Chung: Supervision, Validation, Corresponding author. Phuong Kim Hoang Vuong: Writing, Methodology, Simulation. Ho Truc Ngoc: Conceptualization, Data curation, Visualization. Le Quynh Anh: Literature review, Writing.

Competing interests statement

All contributing authors are based at a Vietnamese university. The policy recommendations in Section 5.3 should be read with this institutional position in mind. Independent replication, including a comparable assessment of Singapore's own roadmap on its own terms, would help confirm whether

the asymmetry holds outside this research team's own vantage point.

Appendix A. Qualitative assessment rubric

Table 3 assigns each dimension one of the following levels. The assignment follows only the documented evidence cited in Table 1, so a rating never rests on general reputation.

- **Nascent:** a target or a feasibility study has been announced, but no legal framework or capital commitment backs it yet.
- **Emerging:** an early-stage regulatory framework has been enacted, or a small-scale pilot project has been verified.
- **Mature:** large-scale commercial operation is active, with use by international shipping lines and third-party verification.
- **Transformative:** a physical resource endowment with no feasible domestic substitute at the competing hub, at a scale verified by independent technical assessment, backed by an enacted legal framework for its commercial use.
- **Structurally constrained:** applies only to the Environment dimension, for a hub whose renewable energy endowment or supporting regulatory framework is limited by physical geography, not by a lack of capital or policy effort. The qualifier signals a disadvantage that further investment cannot close.

For the carbon cost resilience indicator, a Transformative rating means the hub can absorb and offset carbon-related cost through domestic resource autonomy, while a Structurally constrained rating means the hub stays exposed to externally priced energy markets regardless of its technology or governance maturity.

References

- [1] Sun L, Wang X, Hu Z, Ning Z. Carbon and cost accounting for liner shipping under the European Union Emission Trading System. *Front Mar Sci*. 2024;11:1291968. doi:10.3389/fmars.2024.1291968.
- [2] International Carbon Action Partnership. EU Emissions Trading System (EU ETS) [Internet]. Berlin: ICAP Secretariat; 2024 [cited 2026 Oct 26]. ETS factsheet. Available from: <https://icapcarbonaction.com/en/ets/eu-emissions-trading-system-eu-ets>.
- [3] European Parliament and Council of the European Union. Directive (EU) 2023/959 amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading [Internet]. Off J Eur Union. 2023 [cited 2026 Oct 26]. Available from: <https://eur-lex.europa.eu/eli/dir/2023/959/oj>.
- [4] European Parliament and Council of the European Union. Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime) [Internet]. Off J Eur Union. 2023

- [cited 2026 Oct 26]. Available from: <https://eur-lex.europa.eu/eli/reg/2023/1805/oj>.
- [5] PSA International. Annual and sustainability report 2024: a nautical odyssey [Internet]. Singapore: PSA International; 2025 [cited 2026 Oct 26]. Available from: <https://annualreport.globalpsa.com/>.
 - [6] Do TN, Burke PJ, Hughes L, Thi TD. Policy options for offshore wind power in Vietnam. *Mar Policy*. 2022;141:105080. doi:10.1016/j.marpol.2022.105080.
 - [7] Vietnam Meteorological and Hydrological Administration, United Nations Development Programme. Assessment of the technical potential of offshore wind energy in Viet Nam [Internet]. Hanoi: UNDP Viet Nam; 2025 [cited 2026 Oct 26]. Available from: <https://www.undp.org/vietnam/publications/assessment-technical-potential-offshore-wind-energy-viet-nam>.
 - [8] Government of Vietnam. Decree No. 57/2025/ND-CP prescribing the mechanism for direct electricity purchase and sale between renewable energy power generation units and large electricity consumers [Internet]. Hanoi; 2025 Mar 3 [cited 2026 Oct 26]. Available from: <https://thuvienphapluat.vn/van-ban/Thuong-mai/Decree-57-2025-ND-CP-mechanisms-for-direct-power-trading-large-electricity-consumers-647277.aspx>.
 - [9] Veerasamy V, Sampath LPMI, Qiu H, Huang H, Li Y, Nguyen HD, et al. Grid infrastructure and renewables integration for Singapore energy transition. *Sci Rep*. 2025;15(1):34405. doi:10.1038/s41598-025-17376-5.
 - [10] European Commission. Commission Implementing Regulation (EU) 2023/2297 establishing the list of neighbouring container transshipment ports [Internet]. Off J Eur Union. 2023 [cited 2026 Oct 26]. Available from: https://eur-lex.europa.eu/eli/reg_imp/2023/2297/oj.
 - [11] Tran C. VN defines dual-port strategy: Can Gio for global transit, Cai Mep for gateways [Internet]. Hanoi: VietNamNet; 2025 Dec 27 [cited 2026 Oct 26]. Available from: <https://vietnamnet.vn/en/vn-defines-dual-port-strategy-can-gio-for-global-transit-cai-mep-for-gateways-2476295.html>.
 - [12] Prime Minister of Vietnam. Decision No. 148/QĐ-TTg on approval of the investment policy for the Can Gio International Transshipment Port Project. Hanoi; 2025 Jan 16.
 - [13] Li S, Zhu J, Chen P, Li Z, Liao C, Feng W. Exploring high-performance green innovation in China's logistics companies: a TOE framework based on fsQCA. *Front Environ Sci*. 2025;12:1511269. doi:10.3389/fenvs.2024.1511269.
 - [14] Wu X, Khaskheli MB. Systems thinking of marine policies in promoting environmental law, sustainability, and digital technologies: social challenges in Belt and Road Initiative countries. *Systems*. 2024;12(10):400. doi:10.3390/systems12100400.
 - [15] Barney J. Firm resources and sustained competitive advantage. *J Manage*. 1991;17(1):99-120. doi:10.1177/014920639101700108.
 - [16] Barney JB. Looking inside for competitive advantage. *Acad Manag Exec*. 1995;9(4):49-61. doi:10.5465/ame.1995.9512032192.
 - [17] Lagouvardou S, Psaraftis HN. Implications of the EU emissions trading system (ETS) on European container routes: a carbon leakage case study. *Marit Transp Res*. 2022;3:100059. doi:10.1016/j.martra.2022.100059.
 - [18] Meteorological Service Singapore. Climate of Singapore [Internet]. Singapore: National Environment Agency [cited 2026 Oct 12]. Available from: <http://www.weather.gov.sg/climate-climate-of-singapore/>.
 - [19] Nguyen NT, Dang VP, Vo TTBC, Matsushashi R. Techno-economic and environmental assessment of solar and wind-based hydrogen production: a case study in Vietnam. *IEEE Access*. 2025;13:113854-113878. doi:10.1109/ACCESS.2025.3584059.
 - [20] Triantoro W, Mangan J, Rietig K. Towards maritime transport decarbonisation in developing countries: a systematic literature review. *Mar Policy*. 2026;185:106989. doi:10.1016/j.marpol.2025.106989.
 - [21] Gordon JRM, Lee PM, Lucas HC Jr. A resource-based view of competitive advantage at the Port of Singapore. *J Strateg Inf Syst*. 2005;14(1):69-86. doi:10.1016/j.jsis.2004.10.001.
 - [22] Notteboom T, Rodrigue JP. Containerisation, box logistics and global supply chains: the integration of ports and liner shipping networks. *Marit Econ Logist*. 2008;10(1-2):152-174. doi:10.1057/palgrave.mel.9100196.
 - [23] Xing H, Stuart C, Spence S, Chen H. Alternative fuel options for low carbon maritime transportation: pathways to 2050. *J Clean Prod*. 2021;297:126651. doi:10.1016/j.jclepro.2021.126651.
 - [24] Sterman JD. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Boston, MA: Irwin/McGraw-Hill; 2000.
 - [25] Suheri T, Alexandri MB, Raharja SJ, Purnomo M, Viridi S. Interaction between marine sectors using system dynamics for Patimban Deep Sea Port as a green port: a proposed model. *IOP Conf Ser Earth Environ Sci*. 2021;799(1):012021. doi:10.1088/1755-1315/799/1/012021.
 - [26] Peng H, Hao J, Lyu L, Wan S, Tian X, An C. Shore power mitigates the prevailing carbon leakage driven by maritime market-based measures: a dynamic system interpretation. *J Clean Prod*. 2025;499:145243. doi:10.1016/j.jclepro.2025.145243.
 - [27] Long NX, Hung PV. Energy efficiency and carbon emissions assessment of container terminal equipment at Tan Cang – Cai Mep Thi Vai. *Int J Sustain Eng*. 2025;18(1):2580726. doi:10.1080/19397038.2025.2580726.
 - [28] Gemadept Corporation. Sustainability report 2024 [Internet]. Ho Chi Minh City: Gemadept Corporation; 2025 [cited 2026 Oct 26]. Available from: https://www.gemadept.com.vn/wp-content/uploads/2025/04/GMD_Sustainability-Report-2024.pdf.
 - [29] Tang AQ, Mizunoya T. Quantitative approaches for analyzing the potential effectiveness of Vietnam's emissions trading system: a systematic review. *Sustainability*. 2024;16(13):5504. doi:10.3390/su16135504.
 - [30] European Commission. Commission Delegated Regulation (EU) 2024/3214 of 16 October 2024 amending

- Regulation (EU) 2015/757 of the European Parliament and of the Council as regards the rules for the monitoring of greenhouse gas emissions from offshore ships and the zero-rating of sustainable fuels [Internet]. Off J Eur Union. 2024 [cited 2026 Oct 26]. Available from: https://eur-lex.europa.eu/eli/reg_del/2024/3214/oj.
- [31] Government of Vietnam. Decree No. 272/2026/ND-CP on the development-phase procedures for offshore wind power projects [Internet]. Hanoi; 2026 Jul [cited 2026 Oct 26]. Available from: <https://vietstock.vn/2026/07/chinh-phu-ban-hanh-quy-dinh-moi-ve-dieu-kien-khao-sat-dau-tu-dien-gio-ngoai-khoi-768-1463171.htm>.
- [32] International Renewable Energy Agency. Shaping sustainable international hydrogen value chains [Internet]. Abu Dhabi: IRENA; 2024 [cited 2026 Oct 26]. Available from: <https://www.irena.org/Publications/2024/Sep/Shaping-sustainable-international-hydrogen-value-chains>.
- [33] Fasihi M, Breyer C. Global production potential of green methanol based on variable renewable electricity. *Energy Environ Sci*. 2024;17(10):3503-3522. doi:10.1039/D3EE02951D.
- [34] A.P. Moller-Maersk. Astrid Maersk arrives in Shanghai for first green methanol bunkering in China [Internet]. Copenhagen: Maersk; 2024 Apr 10 [cited 2026 Oct 26]. Press release. Available from: <https://www.maersk.com/news/articles/2024/04/10/astrid-maersk-arrives-in-shanghai-for-first-green-methanol-bunkering-in-china>.
- [35] Maritime and Port Authority of Singapore. Singapore opens applications for methanol bunkering licence [Internet]. Singapore: MPA; 2025 Mar 26 [cited 2026 Oct 26]. Media release. Available from: <https://www.mpa.gov.sg/media-centre/details/singapore-opens-applications-for-methanol-bunkering-licence>.
- [36] European Commission. Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin [Internet]. Off J Eur Union. 2023 [cited 2026 Oct 26]. Available from: https://eur-lex.europa.eu/eli/reg_del/2023/1184/oj.