

Research Article

Governance of marine biofuels as a transitional fuel for Thailand's shipping decarbonization: Ensuring Well-to-Wake integrity through a Triple-Layer assurance framework

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Abstract: Drop-in marine biofuels are frequently presented as a near-term bridge for shipping because they may leverage existing engines and bunkering infrastructure. Yet climate benefit is not inherent to the biofuel label: well-to-wake (WtW) outcomes vary substantially across feedstocks, conversion routes, process-energy sources, logistics, and methodological assumptions. This paper develops a governance-oriented approach for Thailand to deploy marine biofuels as a transitional fuel while safeguarding WtW integrity and avoiding lock-in. We conducted an evidence-informed policy analysis using a targeted scoping review of English-language scholarly literature and official policy documents published between 2010 and 2026. The initial corpus comprised 42 sources identified through targeted searches and source tracing. Following reviewer feedback requesting a Thailand-specific case application, three additional official/context sources were added during revision. The final corpus therefore comprised 33 sources retained from 45 sources screened against eligibility criteria: 21 topical peer-reviewed studies, nine official/regulatory/context documents, and three methodological references. Sources were included when they addressed marine biofuel pathways or directly relevant maritime fuel governance and provided evidence on WtW/LCA, techno-economics, market dynamics, operability, or policy instruments. The synthesis shows that volumetric blending targets are a weak proxy for credible mitigation when traceability and verification are not institutionalized. The central contribution is a triple-layer assurance framework integrating operability/fuel-quality assurance, traceability/chain-of-custody assurance, and WtW climate-integrity assurance. Applied to Laem Chabang Port, the framework identifies a practical regulatory sandbox sequence for pilot-to-scale deployment through fuel-quality control, batch-level traceability, and WtW-based monitoring, reporting, and verification (MRV).

Keywords: Marine biofuels; Transitional fuel; Well-to-wake; Traceability; Assurance

1. Introduction

Shipping is a capital-intensive sector with long asset lifetimes and slow infrastructure turnover. These structural characteristics make fuel transitions slower than in many other transport segments. Although near-zero/zero-carbon fuels are often framed as end-state solutions, near-term deployment remains constrained by cost and readiness. Transitional fuels therefore remain policy-relevant, provided they deliver credible mitigation and are governed to avoid transitional-path lock-in. [1-3]

Marine biofuels-particularly drop-in candidates-are frequently proposed for this bridging role because they may be introduced with limited hardware changes. However, WtW mitigation is pathway-dependent: feedstock provenance, conversion route, process-energy sources, logistics, and co-product

handling can materially change outcomes. [1,4-6] This variability makes governance (not merely availability) decisive: volume-based incentives may yield non-credible outcomes when WtW accounting is inconsistent and supply chains are not auditable.

To avoid ambiguity, this paper uses 'drop-in marine biofuels' to refer to renewable liquid fuels that can be blended into (or substitute for) conventional marine distillates with limited hardware changes, subject to operability constraints. Illustrative candidates include FAME biodiesel blends, HVO/renewable diesel, and paraffinic drop-in fuels such as biomass-to-liquid Fischer-Tropsch diesel, depending on final fuel properties and blending requirements. Fuel-property evidence comparing alternative drop-in candidates and blends against standard marine diesel further indicates that blend behavior and storage/compatibility issues (including corrosion-related concerns in some cases) should be treated as an operability gate rather than an afterthought. [6-7]

Evidence from emerging supply-chain configurations (e.g., agrarian biohubs) indicates that technology choice and scale can create non-trivial cost-GHG trade-offs for marine biofuel pathways, reinforcing the need for pilot-to-scale decision gates rather than unconditional expansion. [2]

Thailand-specific governance gap. The central challenge is therefore not 'whether biofuels exist,' but how to govern transitional biofuel deployment through an assurance architecture that integrates (i) WtW climate integrity, (ii) auditable traceability, and (iii) operability/fuel-quality safeguards into a coherent pilot-to-scale pathway. This study addresses that gap by synthesizing peer-reviewed evidence into a triple-layer assurance framework, supported by international benchmarking and a Laem Chabang Port case application. [9], [18]

2. Method

2.1 Study design and reporting orientation

This study employs an evidence-informed policy analysis grounded in a targeted scoping review, complemented by thematic synthesis and evidence mapping. The review is reported using PRISMA-ScR as a reporting orientation to strengthen transparency and auditability (eligibility criteria, information sources, selection, and data charting). The synthesis follows established thematic synthesis procedures (coding -> descriptive themes -> analytical themes) consistent with qualitative evidence synthesis practice. [19-21]

2.2 Information sources and search strategy

The literature search was conducted using a targeted scoping strategy rather than an exhaustive systematic-review design. Bibliographic databases and publisher platforms searched included Scopus, Web of Science, ScienceDirect, and Google Scholar. IEEE Xplore was checked at the scoping stage using maritime decarbonization and fuel-governance keywords, but it was not retained as a core source because the final review question focused on fuel pathways, WtW/LCA, operability, market dynamics, and governance rather than electrical/control-system engineering. The search covered English-language scholarly publications and official documents published between January 2010 and June 2026. Search terms combined four concept groups: (i) marine biofuels and drop-in candidates (FAME, HVO/renewable diesel, Fischer-Tropsch/BTL, bio-LNG, biomethanol), (ii) well-to-wake, life-cycle assessment, GHG intensity, and carbon accounting, (iii) traceability, chain of custody, verification, MRV, and certification, and (iv) policy instruments, regulatory sandbox, port implementation, and maritime fuel transition. Official documents were identified from IMO, EUR-Lex, Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT), the Maritime and Port Authority of Singapore (MPA), Laem Chabang Port/PAT, and other relevant government sources. Records were eligible when they provided policy-actionable evidence for at least one synthesis domain: WtW/LCA variability, techno-economics, market dynamics, operability/fuel quality, traceability, or governance implementation.

2.3 Eligibility criteria

Inclusion. Sources were included if they (1) address marine biofuels (including drop-in candidates) or marine fuel pathways directly relevant to marine biofuels; and (2) provide evidence on at least one domain: (a) WtW/LCA outcomes or drivers of variability, (b) techno-economics/competitiveness, (c) market/commodity dynamics affecting supply reliability, (d) operability/fuel-quality constraints, or (e) policy instruments/adoption dynamics. **Exclusion.** Non-scholarly opinion pieces, sources lacking rele-

vance to marine deployment/governance, and sources without policy-actionable implications were excluded. Official documents were included only when they provided regulatory, programmatic, or implementation evidence relevant to marine fuel governance.

2.4 Screening and selection process

A corpus-based PRISMA-ScR-style flow was used to document the source selection process (Figure 1). The initial targeted searches and source tracing identified 42 sources for initial consideration. These sources were screened for relevance to marine biofuels, WtW/LCA integrity, fuel operability, market and policy dynamics, and governance mechanisms. Twelve sources were excluded at the preliminary screening stage because they were not directly relevant to marine fuel deployment, governance, WtW assessment, or policy-actionable implications. Following reviewer feedback requesting a Thailand-specific case application, three additional official/context sources related to Thailand's port and maritime context were identified and added during revision. As a result, 45 sources were screened in total. Thirty-three full-text sources were assessed for eligibility and retained in the final synthesis and case-application corpus. The final corpus comprised 21 topical peer-reviewed studies, 9 official/regulatory/context documents, and 3 methodological references. No full-text source was excluded after eligibility assessment because full-text review was conducted on a pre-screened, relevance-focused corpus. The flow is intentionally presented as a corpus-based PRISMA-ScR-style flow rather than as a database-exhaustive systematic-review flow.

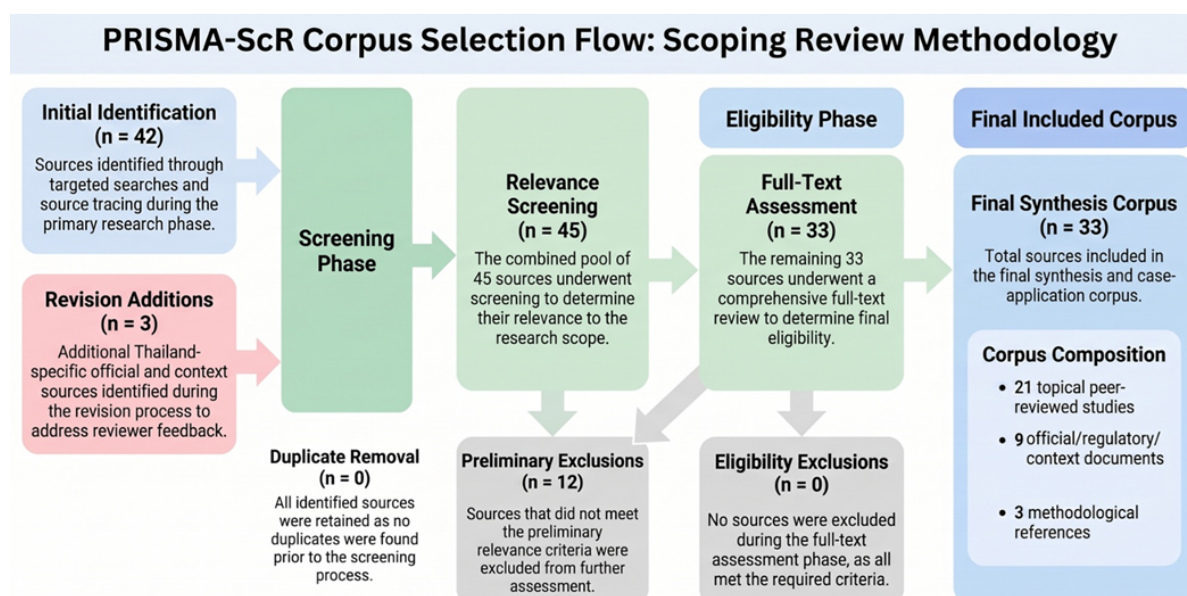


Figure 1. PRISMA-ScR-style corpus flow for the targeted scoping review.

Note: Corpus-based flow for a targeted scoping review; this is not a database-exhaustive systematic review. The three additional Thailand-specific sources were added during revision to address the reviewer's request for a Thailand-specific case application.

2.5 Data charting and synthesis

A structured data-charting form extracted bibliographic details; country or analytical context; fuel/pathway characteristics; system boundaries and key assumptions; drivers of WtW outcomes (feedstock, process energy, logistics, allocation); operability constraints; market/cost determinants; and policy implications. Evidence was synthesized into four policy-actionable clusters: (i) WtW drivers and LCA comparability, (ii) cost/market drivers, (iii) operability/fuel-quality gates, and (iv) policy levers/adoption barriers. [20-21]

2.6 Quality appraisal / risk-of-bias considerations

Although scoping reviews do not always require formal risk-of-bias scoring, we incorporated a methodological limitations appraisal to strengthen credibility. We assessed transparency and potential

bias using fit-for-purpose criteria, including clarity of system boundary/assumptions (WtW/LCA), transparency of data sources/parameters, treatment of uncertainty/sensitivity, and disclosure of conflicts of interest where stated. Appraisal results were used to weight confidence in synthesized themes (high/medium/low) rather than to exclude studies mechanically, consistent with the mapping intent of scoping reviews. [21]

2.7 Outputs

Outputs include: (1) a summary table of reviewed studies, (2) a triple-layer assurance framework, (3) a decision-gate pilot-to-scale roadmap suitable for regulatory sandboxes, (4) a Thailand-specific Laem Chabang Port case application, and (5) a conceptual governance framework diagram.

3. Results and Discussion

3.1 Evidence base and characteristics of reviewed studies

The final evidence corpus comprised 33 sources: 21 topical peer-reviewed studies, 9 official/regulatory/context documents, and 3 methodological references. Table 1 summarizes the topical peer-reviewed studies used to construct the evidence base for WtW integrity, market and cost drivers, operability risks, and port-transition governance. The additional official/context sources were used to support the Thailand-specific Laem Chabang Port case application.

Table 1. Summary of reviewed topical studies.

Author(s)	Country/context	Fuel type/pathway	Study findings	Key insights
de Souza & Seabra (2024)	Brazil	HVO, HDPO, ethanol, ammonia; bulk carrier	Biofuels reduced GHG but increased MFSP/LCOS versus LSFO.	Biofuels need incentives and pathway screening before scale.
Chandrasekaran et al. (2026)	Spain, Colombia, Namibia	HTL-derived marine biofuels from field residues	Agrarian biohubs show cost-GHG trade-offs and context sensitivity.	Pilot-to-scale gates should consider local supply-chain capabilities.
Salameh et al. (2025)	Experimental fuel-quality context	Renewable gasoline biofuel/additives	Fuel formulation and quality control determine performance.	Fuel-quality assurance is a prerequisite for operational pilots.
Robalo-Cabrera et al. (2025)	Global/review	Alternative fuels and decarbonisation measures	Decarbonisation requires integrated fuel, operational, and policy measures.	No single fuel pathway is sufficient; governance packages matter.
Watanabe et al. (2022)	Norway	Drop-in biofuels for deep-sea shipping	Prospective LCA shows high mitigation potential but pathway sensitivity.	WtW assumptions must be transparent before policy use.

Kazmi et al. (2024)	South Korea/experimental	Waste coffee-ground pyrolysis bio-oil	Upgrading can improve marine biofuel quality and HHV.	Technical upgrading can support operability if quality gates are met.
Manikandan et al. (2025)	Global/review	Biofuel innovations for marine propulsion	Biofuels may lower black carbon emissions under controlled conditions.	Emission benefits require operational verification.
Barone et al. (2026)	Fleet/vessel-class modelling	LNG, methanol, bio/e-fuel variants	Fuel choice depends on vessel class, route, infrastructure, and incentives.	Policy design must link fuel pathways to operational realism.
Bouter et al. (2025)	EU	Liquid biofuels under RED II/III	Updated GHG values show variability and data uncertainty.	Standardized carbon accounting is central to climate integrity.
Galimova et al. (2025)	Maritime and aviation	e-fuels and biofuels	Sustainable fuel adoption differs by sector and cost assumptions.	Policy instruments must be sector-specific and investment-legible.
de Paula Leite et al. (2025)	Portugal/EU	Biofuel adoption and RED policy	Policy mechanisms interact with energy and agricultural markets.	Adoption policies need stability and traceable compliance.
Montuori et al. (2025)	European ports	Port sustainability actions	Ports deploy OPS, renewables, hydrogen, biofuel, and digital measures.	Port-level KPIs can operationalize sustainability strategies.
de Paula Leite (2025)	EU market	UCOME/second-generation biofuel	Commodity interdependence can affect advanced biofuel pricing.	Procurement needs market-risk management.
Harahap et al. (2023)	Sweden	Biomethanol, hydrogen, e-fuels	Policy instruments and supply-chain optimization influence transition pathways.	Hybrid techno-economic and socio-technical governance is useful.

Mercado-Cordova (2025)	Global	Advanced biofuels	Learning/spillovers lower costs but feedstock constraints remain.	Scale-up must account for biomass availability and learning effects.
Solakivi et al. (2022)	EU/regulatory context	Biofuels and electrofuels	Cost-optimal pathway may move from fossil fuels via biofuels to electrofuels.	Biofuels can be transition fuels under regulation.
Roux et al. (2024)	Global/review	Maritime fuels LCA	LCA studies lack transparency and comparable boundaries.	WtW governance should require disclosure of assumptions.
Trypolska (2024)	Ukraine	Bioethanol and biodiesel	Market uptake depends on mandate, tax, and fuel-demand conditions.	Market structure and policy signals shape adoption.
Bullermann et al. (2024)	Fuel-property testing	FAME, OME, HVO, FTD, HDO blends	Blend compatibility, corrosion, stability, and distillation behavior vary.	Operational pilots need fuel-specification and compatibility monitoring.
Atofarati & Enweremadu (2026)	Global/review	Nanoparticle additives/catalysts	Nano-additives can improve properties but create dispersion and EHS concerns.	Additives require safety and monitoring governance.
Schulz et al. (2025)	Australia/Port of Newcastle	Port-based biofuel diversification	Ports can become circular biofuel hubs using hinterland bio-waste.	Port transition planning should link logistics, demand, and policy.

3.2 WtW variability and LCA comparability: the credibility problem

Prospective and pathway-specific evidence indicates that drop-in biofuels' WtW performance is highly sensitive to upstream parameters-feedstock choice, process energy sources, logistics, and co-product allocation-leading to material dispersion in reported mitigation outcomes. [5] Assessments of specific production contexts reinforce that upstream energy and supply-chain configuration can dominate WtW outcomes. [1], [4] Review evidence further cautions that inconsistent boundaries and assumptions undermine comparability across studies and fuels, producing governance risk if policy relies on non-transparent calculations. [6] Credible deployment therefore requires standardized WtW accounting and transparent assumptions aligned with IMO life-cycle guidance. [14]

3.3 Competitiveness, supply reliability, and market volatility

Competitiveness under evolving regulatory regimes remains a primary determinant of adoption. [3] This issue is not merely theoretical. In Sweden, renewable marine fuel supply-chain modelling found that biomethanol became cost-effective only when the carbon price exceeded approximately 100 EUR/tCO₂, while hydrogen-based marine fuels required stronger carbon-price signals of more than 200 EUR/tCO₂, illustrating how policy design can determine whether renewable marine fuel pathways move from pilot to commercial uptake. [23] In Portugal, evidence on biofuel adoption under the Renewable Energy Directive shows that regulatory instruments interact with agricultural and energy market prices as well as fossil-fuel stocks; this indicates that renewable-fuel incorporation can remain structurally dependent on conventional market conditions even under policy mandates. [24] Evidence from Ukraine's liquid biofuel market further demonstrates how blending mandates, excise-tax design, and domestic market structure shape uptake potential. [25] At the commodity level, interdependence between agricultural feedstocks and second-generation biofuel prices can create volatility and supply-risk exposure, particularly for waste- and residue-based pathways. [26,27] For Thailand, these empirical lessons imply that a marine biofuel pilot should not rely on a simple volumetric target alone. A Laem Chabang Port sandbox should instead combine limited-volume procurement with verified WtW thresholds, feedstock-origin documentation, and contract mechanisms that allocate market-price and supply-continuity risks among fuel suppliers, vessel operators, port authorities, and regulators. Implication: pilots should be paired with risk-aware procurement and outcome-based incentives tied to verified performance rather than volumes.

3.4 Operability and fuel-quality gates before scale

Operability constraints—stability, sludge/contamination control, and compatibility—can become binding, particularly during pilot phases. [28, 29] Evidence on fuel-quality control and upgrading pathways reinforces that meeting operational requirements is as important as carbon metrics. [22, 28] Beyond baseline specifications, additive-enabled approaches (including nanoparticle-based additives) have been reviewed as potential tools to improve key fuel properties (e.g., oxidative stability); however, governance must explicitly consider dispersion stability, handling safety, and unintended environmental/health risks prior to operational adoption. [30] Pilots should formalize fuel specifications, onboard handling protocols, monitoring, and incident reporting to institutionalize learning.

3.5 Expanded triple-layer assurance framework and decision gates

The proposed triple-layer assurance framework translates the evidence synthesis into operational governance. The framework is designed to prevent the common failure mode in transitional-fuel policy: treating a fuel label or blending volume as a proxy for mitigation. Instead, scale-up is allowed only when all three layers pass predefined decision gates.

Table 2. Evidence map linking drivers, failure modes, and policy levers.

Evidence cluster	Key drivers	Failure modes	Policy levers	Evidence
WtW/LCA variability	Feedstock, process energy, logistics, allocation/co-products	Non-credible mitigation / wrong pathway choice	WtW threshold + assumption disclosure + verification	[4], [5], [6], [14]
LCA comparability	Inconsistent boundaries/assumptions	Numbers-based greenwashing	Standardized LCA/WtW + transparency	[6], [14], [31]
Sustainability & integrity	Feedstock origin and traceability	ILUC / misattribution / double counting	Chain-of-custody + audit + registry	[23], [24], [26]
Competitiveness	Feedstock/energy prices, learning effects	Slow uptake	Outcome-based incentives + pilot contracts	[3], [27], [32]

Market dynamics	Commodity interdependence, volatility	Pilot disruption	Diversification + contracting/hedging	[25], [26], [27]
Operability gate	Stability, sludge/contamination, compatibility	Operational failure	Fuel specs + onboard protocols + monitoring	[7], [22], [28], [29], [30]
Pathway trade-offs	Technology/scale trade-offs cost-GHG-scalability	Scale-up lock-in	Decision gates: pilot -> scale only if pass	[1], [8], [33]
Adoption & governance	Policy certainty + package design	Slow adoption / lock-in	Policy package + phased roadmap + MRV institutions	[1], [24], [33]
Benchmarking	EU verification; JP staged pilots; SG incentives	Inappropriate policy transfer	Hybrid approach for Thailand	[9]-[13]
Port transition	Logistics + demand aggregation + sequencing	Stranded pilots / stranded assets	Port sandbox + corridor procurement + MRV integration	[15]-[18]

Table 3. Triple-layer assurance framework: responsible organizations, monitoring mechanisms, and KPIs.

Assurance layer	Potential responsible organizations/agencies	Verification and monitoring mechanisms	Performance indicators (KPIs)	Evidence
Operability / fuel-quality assurance	Marine Department (safety and regulatory oversight); Port Authority of Thailand/Laem Chabang Port (port interface); ship operators; accredited fuel laboratories	Pre-bunkering certificate of analysis; blend compatibility testing; storage/stability tests; onboard handling protocol; incident and sludge/contamination reporting	Fuel batch meeting specifications; zero critical safety incidents; stable storage performance; documented onboard handling; successful engine/auxiliary performance during pilot	[7], [22], [28], [29], [30]
Traceability / chain-of-custody assurance	Fuel suppliers; bio-fuel producers; third-party verifiers; customs/port digital systems; designated registry operator	Mass-balance or segregation records; feed-stock origin documentation; batch registry; audit trail; third-party verification; double-counting checks	100% batch-level documentation; complete chain-of-custody record; no duplicate claims; verifier sign-off; data availability for audit	[6], [23], [24], [26]

Climate-integrity / WtW assurance	Policy lead agency; Marine Department; accredited LCA/MRV verifier; IMO-aligned technical committee	Standardized WtW calculation; transparent system boundaries; sensitivity/uncertainty disclosure; comparison against eligibility threshold; annual MRV report	Verified WtW GHG intensity; percentage reduction versus fossil comparator; completeness of assumptions; uncertainty disclosed; compliance with IMO LCA guidance	[5], [6], [9], [14]
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Decision-gate roadmap. A pilot should proceed to scale only if (i) operability indicators meet thresholds, (ii) traceability/audit trails are complete, and (iii) verified WtW performance meets the program's eligibility criteria. This reduces lock-in risk, improves investor confidence, and allows regulators to learn from real-world operations before wider deployment.

3.6 Thailand-specific case application: Laem Chabang Port as a regulatory sandbox

This case application is an illustrative analytical scenario developed by the author to demonstrate how the proposed assurance framework could be operationalized in a Thai port context. It does not imply that the Government of Thailand, the Marine Department, the Port Authority of Thailand, Laem Chabang Port, or any other public agency has adopted, endorsed, approved, or decided to implement the proposed framework.

Laem Chabang Port is selected as a Thailand-specific case application because it is Thailand's main deep-sea port and offers a more suitable pilot environment for verified marine biofuel deployment than a purely riverine or urban port setting. Official port information identifies Laem Chabang Port as covering 2,572 acres and providing multiple terminal functions, including seven container terminals, a multipurpose terminal, a Ro/Ro terminal, a passenger and Ro/Ro terminal, a general cargo terminal, and a shipyard terminal. [16] The port is also described as a landlord port in which the Port Authority of Thailand is responsible for the whole port while private operators perform operational functions. [31]

This landlord-port structure is relevant to the proposed assurance framework because it allows responsibilities to be distributed across regulator, port authority, terminal operator, ship operator, fuel supplier, laboratory, and third-party verifier. The Port Authority of Thailand has also been reported as pursuing plans to convert five ports into smart and green ports by 2030, including measures related to logistics connectivity, digital platforms, and carbon-neutrality planning. [17] In parallel, Laem Chabang Port Phase 3 is expected to increase capacity, introduce five new berths and two rail freight yards, and support automated cargo-handling systems. [18] These features make Laem Chabang Port an appropriate sandbox for testing biofuel governance before broader national application.

Proposed sandbox design. As an analytical proposal, the sandbox could begin with a limited-volume pilot for a defined vessel segment or service pattern, such as port service craft, terminal support operations, or a selected coastal/inter-port route linked to Laem Chabang. The pilot would not approve a fuel simply because it is bio-based; instead, every batch would be tested against the triple-layer assurance framework. Potential roles could be distributed as follows: the Marine Department could provide maritime safety and regulatory oversight; the Port Authority of Thailand and Laem Chabang Port could coordinate port-side data interfaces and operational logistics; fuel suppliers and accredited laboratories could provide fuel-quality certificates; and third-party verifiers could check chain-of-custody and WtW accounting. These roles are proposed for scholarly analysis and do not represent official agency assignments or commitments.

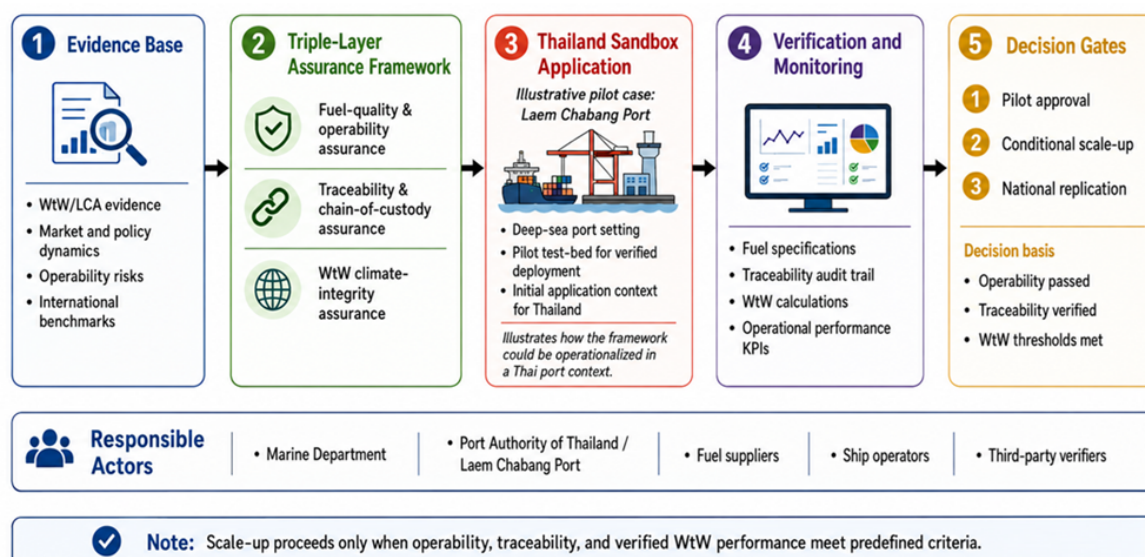
KPIs for the Laem Chabang sandbox. For analytical purposes, minimum KPIs could include: (1) 100% fuel batch certificate of analysis before bunkering; (2) completion of compatibility/stability tests for each approved blend; (3) no critical safety or engine-operability incident during the trial; (4) complete chain-of-custody record for all biofuel feedstock and product batches; (5) verified WtW GHG intensity and comparison with a fossil comparator; (6) transparent disclosure of WtW assumptions and uncertainty; and (7) port-side data submission within a defined reporting cycle. If the KPIs are met, the pilot

could progress to a larger corridor or wider procurement program; if not, scale-up would be delayed pending corrective measures.

Relationship to Bangkok Port and coastal shipping. Bangkok Port and coastal shipping remain important follow-up applications. Bangkok Port can test an urban-port application where congestion, land constraint, and local air-quality benefits are central; coastal shipping can test operational repeatability and corridor procurement. However, Laem Chabang Port is more suitable as the initial sandbox because its deep-sea, multimodal, and private-operator structure better represents the governance complexity of international marine fuel transition.

3.7 Conceptual governance framework

Figure 2 illustrates the proposed governance logic as an author-developed conceptual framework. Evidence synthesis and the Thailand-specific port context feed into three assurance layers: operability/fuel-quality assurance, traceability/chain-of-custody assurance, and climate-integrity/WtW assurance. These layers are implemented through a regulatory sandbox and decision gates. Only fuels and deployment models that pass the defined KPIs proceed from pilot to scale. The figure is intended as an analytical tool for scholarly discussion, not as an official implementation plan of any government agency.



Author-developed conceptual synthesis for scholarly discussion.

Figure 2. Conceptual governance framework for verified marine biofuel deployment in Thailand.

4. Conclusions

This study concludes that marine biofuels can be useful transitional fuels for Thailand only when deployment is governed as a verified decarbonization pathway rather than as a volume-based substitution exercise. The main policy implication is that Thailand could begin with a controlled port-based sandbox, with Laem Chabang Port serving as an illustrative candidate case, where fuel quality, chain-of-custody documentation, and WtW GHG intensity can be tested together before scale-up. The proposed triple-layer assurance framework translates this requirement into three operational layers: operability/fuel-quality assurance, traceability/chain-of-custody assurance, and WtW climate-integrity assurance. This integrated approach reduces the risk of greenwashing, double counting, unsafe fuel handling, and premature lock-in. For policymakers, the priority is not to select one biofuel pathway in advance, but to establish decision gates, responsible-agency coordination, monitoring mechanisms, and KPIs that allow only verified pathways to move from pilot to wider deployment. For ports and vessel operators, the framework provides a practical sequence for learning-oriented implementation: test, ver-

ify, correct, and scale only when performance criteria are met. The proposed pathway should be understood as the author's academic synthesis and not as an official decision or commitment by the Government of Thailand, the Marine Department, the Port Authority of Thailand, or Laem Chabang Port.

5. Author note / disclaimer

The governance framework, regulatory sandbox design, and Laem Chabang Port case application proposed in this article are the author's academic synthesis based on reviewed literature, official public documents, and policy analysis. They are intended for scholarly discussion and do not represent the official position, policy, decision, endorsement, or implementation commitment of the Government of Thailand, the Marine Department, the Port Authority of Thailand, Laem Chabang Port, or any other government agency.

6. Patents

Author Contributions: For research articles, P.S. Conceptualized the study, S.S. and P.S. supervised the research, data curation and formal analysis were carried out by P.S. The original draft was prepared by P.S., with review and editing by J.W. and P.S. All authors have read and agreed to the published version of the manuscript.

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