Transportation Research Part D 162 (2027) 105713

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

From commitment to implementation: policy pathways for green shipping corridors☆

Hanwen Fan, Zaili Yang *

Liverpool Logistics Offshore and Marine Research Institute, Liverpool John Moores University, Liverpool, UK

ARTICLE INFO

Keywords:
Maritime decarbonization
Green shipping corridors
Text mining
Complex network
Sustainable shipping

ABSTRACT

Despite rapid growth in green shipping corridor (GSC) commitment, the translation of policy ambitions into operational practice remains deeply uneven across regions. Addressing this policy-critical gap, this study investigates the structural bottlenecks that impede GSC implementation through a comparative analysis of global and regional development trajectories. By integrating text mining with complex network analysis, the study systematically identifies and maps how bottleneck configurations diverge across institutional and geographic contexts. The findings reveal that GSC development is not a uniform transition process, but a regionally differentiated and stage-dependent system requiring targeted policy responses. Critically, the study derives evidence-based, region-specific policy insights that are difficult to capture through conventional approaches, offering actionable guidance for policymakers seeking to close the gap between regulatory ambition and corridor-level realization. The findings will support stakeholders in designing differentiated policy interventions and advancing the transition of GSCs from conceptual commitments to practical implementation.

1. Introduction

Green shipping Corridors (GSCs) have emerged as a cornerstone of global maritime decarbonization strategy, representing a systemic framework of designated shipping routes and port clusters to catalyze the transition from fossil-based marine fuels to zero-emission energy trajectories (Lyu et al., 2026, Ismail et al., 2024). Against the backdrop of the IMO's increasingly stringent greenhouse gas strategies and the 2022 Clydebank Declaration, participation in GSC initiatives has increased substantially, with reported projects rising from around 20 in 2022 to over 80 by 2025, involving more than 300 stakeholders globally (Global Maritime Forum, 2025). This rapid increase not only reflects growing stakeholder commitment and active participation in GSC development, but also signals enhanced coordination and expectations for their future implementation (Mærsk, 2022). However, this rapid growth also masks a more pressing policy challenge: the gaps between commitment and realization is widening, and existing policy frameworks have not kept pace with the structural bottlenecks of corridor development across heterogeneous regional contexts.

The benefits of the GSC implementation are clear and contributes to the economic and trade, environmental-friendly, and health and social conditions (Garg et al., 2025, Lee et al., 2026). However, this apparent global convergence relies on a complex and heterogeneous reality. In practice, global GSCs discourse primarily operates at a macro level by articulating shared decarbonization

☆ This article is part of a special issue entitled: 'Integrated maritime' published in Transportation Research Part D.

* Corresponding author at: Liverpool John Moores University, School of Engineering, Technology and Maritime Operations, Byrom Street, Liverpool L3 3AF, United Kingdom.

E-mail address: Z.Yang@ljmu.ac.uk (Z. Yang).

https://doi.org/10.1016/j.trd.2026.105713
Received 1 May 2026; Received in revised form 14 September 2026; Accepted 23 October 2026
Available online 27 October 2026
1361-9209/© 2026 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

ambitions, sharing targets, common principles, and calls for cooperation among international institutions. By contrast, regional GSCs reports tend to focus on micro-level processes through translating the global ambitions into regional route-specific decisions on specific topics including but not limited to alternative fuels pathways, bunkering infrastructure update and investment, policy-making, investment decisions and financial mechanisms. Regional GSCs initiatives therefore not only operationalize the global visions but also reveal more the practical bottlenecks arising during the implementation stages.

This macro-to-micro translation occurs across different GSCs situated within different geographic and economic settings, ranging from short-sea ferry routes within European regions to deep-sea bulk commodity corridors connecting Australia and East Asia, and intercontinental container routes linking North America with Asia. Each corridor operates within distinct regulatory environments, confronts different infrastructure constraints, alternative fuels availability, and engages with fundamentally different stakeholder ecosystems. In terms of their maturity levels, some show superiority over the others. As a result, these structural differences shape distinct transition logics, whereby corridor development is governed by region-specific combinations of technological feasibility, institutional capacity, and market conditions, rather than a unified global implementation pathway (Dolatabadi et al., 2025). Consequently, what is framed as a unified global transition agenda may in practice be advancing along divergent regional development pathways, shaped by localized bottleneck configurations rather than a common implementation logic.

This divergence is made starkly visible by the uneven realization of GSC commitments. Critically, this gap between commitment and realization is not uniformly distributed across regions. The Asia-Pacific region has concentrated its development efforts around ammonia-powered bulk shipping tied to commodity trade flows, while the Trans-Atlantic and European region has progressed furthest in operational scaling through institutional maturity and regulatory enforcement. Trans-regional long-distance corridors, such as Shanghai to Los Angels remain constrained by cross-border governance complexity and techno-economic feasibility challenges that differ fundamentally from those faced by intra-regional initiatives (Cities, 2022). These patterns suggest that the fragmented realization of GSCs cannot be fully captured by generic references to technical or financial barriers alone, but also reflects regionally differentiated development logics. This has direct consequences on generic uniform policy-driven frameworks are likely to misalign with the specific bottleneck configurations that constrain individual corridors, resulting in misdirected investment, regulatory friction, and stalled implementation. Effective policy design for GSCs therefore requires a systematic, evidence-based understanding of how barriers differ across regions and development stages. Accordingly, this study addresses the following research questions (RQ).

RQ1: How does global GSC discourse differ from regionally embedded corridor discourse in terms of thematic emphasis?

RQ2: To what extent do different regional or corridor types exhibit distinct bottleneck structures across fuel, infrastructure, demand, and governance policy dimensions?

RQ3: How do these regional divergences help explain the fragmented and uneven realization of global maritime decarbonization?

To address the above research questions, this study develops a data-driven, corpus-based analytical framework integrating natural language processing (NLP) techniques and complex network (CN) analysis. The framework is applied to a multi-source GSC corpus, including global and regional development reports, governmental white papers, and industry publications from maritime organizations and consultancy firms. Specifically, the framework extracts key terms, bi-gram structures, and co-occurrence networks to identify thematic patterns and potential bottlenecks across regions. By systematically quantifying keyword distributions and bottleneck structures, the framework reveals both commonalities and divergences in GSC commitments, providing an evidence-based foundation for understanding the transition from policy ambition to practical implementation. Critically, the analytical outputs are oriented towards policy relevance: by mapping how bottleneck structures differ across regions and development stages, the study generates region-specific, actionable guidance intended to support policymakers and industry stakeholders in moving GSC commitments from declaration to practice. The main core policy and methodological contributions of this study are summarized as follows:

(1) This study constructs a multi-level GSC corpus covering global and regional reports from 2021 to 2025, including Global Maritime Forum reports, governmental white papers, and industry documents. This corpus provides a structured empirical basis for identifying bottlenecks in GSC development from both global and regionally embedded perspectives.
(2) This study develops an integrated NLP and CN framework to systematically quantify keyword importance, bi-gram patterns, and co-occurrence structures. This approach enables the identification of region-specific thematic priorities and the structural relationships among key development factors, thereby revealing differentiated bottleneck configurations across regions.
(3) This study establishes a data-driven analytical linkage between thematic similarity patterns and regional policy priorities, providing actionable and valuable insights to support the design and implementation of GSCs based on region-specific development pathways.

The structure of the remainder of this paper is organized as follows. Section 2 introduces the literature. Section 3 describes the research modelling for GMCs keywords and bottlenecks identification. Following that, an empirical analysis is conducted in Section 4. Section 5 discusses the findings of this paper and gives implications, and Section 6 concludes this study and gives future direction.

2. Literature review

Given that the research on GSCs is still in its nascent stage, a comprehensive review of extant literature was conducted to consolidate the current state of knowledge. This section is organized into three thematic subsections as follows.

2.1. Evolution of GSCs: concepts and policy frameworks

The term “Green corridor” has found some applications in various domains, including the rail and air transportation, wildlife zones, and urban city designs (Zhou and Zhai, 2026, Yan, 2024, Faivre et al., 2018). The formal emergence of GSCs as a central instrument in maritime decarbonization can be traced back to the announcement of the Clydebank Declaration (2021).[1] Signed by 24 nations, this initiative set an initial target of establishing at least six GSCs by the mid-2020 s, scaling up to more extensive routes by 2030. Within this context, GSCs are strategically designed to bridge the gaps among the GSCs deployment by concentrating zero-emission fuels and technologies on specific maritime trade routes. The legitimacy of GSCs is anchored in a multi-layered policy structure, including the Paris Agreement, IMO Resolution MEPC.304(72), and MARPOL Annex VI, forming a comprehensive framework that integrates climate pledges with technical standards and port infrastructure requirements (Song et al., 2025).

Understanding the evolution of GSCs concept further requires situating them within a broader lineage of corridor-based concepts. As noted by Song et al. (2025), GSCs extend the logic of Green Transport Corridors and Green and Digital Corridors, originally advocated in the EU's Freight Transport Logistics Action Plan.[2] While these earlier concepts emphasized efficiency, intramodality, and digitalization, the contemporary interpretation of GSCs, particularly as articulated by the Global Maritime Forum, places stronger emphasis on collaboration among public and private stakeholders for large-scale implementation (Global Maritime, 2021). In this formulation, GSCs function not only as planning instruments but also as experimental platforms aimed at demonstrating the technical and economic feasibility of zero-emission shipping, a definition that has subsequently been adopted by international initiatives such as C40 Cities and DNV (Cities, 2022, DNV, 2023).

As GSCs have transitioned from conceptual frameworks to operational initiatives, their underlying structure has become increasingly complex. Existing studies and governmental documents indicate that corridor development is shaped by multiple value dimensions, including environmental performance, investment attractiveness, and broader socio-economic considerations such as local community well-being (Garg et al., 2025). At the same time, the involvement of diverse stakeholder groups also introduces heterogeneous priorities and coordination challenges. These complexities are further reflected in unresolved issues related to cost-sharing mechanisms, financing arrangements for zero-emission vessels, and the reliability of green fuel supply chains (Song et al., 2025). Such dynamics suggest that the evolution of GSCs is not merely technological or infrastructural, but also institutional, characterized by increasing interdependence across actors and decision-making levels.

This growing complexity is further amplified by the interaction between global regulatory frameworks and region-specific policy instruments. While the International Maritime Organization (IMO) provides overarching targets and standards for maritime decarbonization, regional initiatives have emerged to accelerate implementation through more immediate and context-specific measures. For example, the EU’s FuelEU Maritime regulation and the extension of the Emissions Trading System (ETS) introduce explicit carbon pricing mechanisms within regional jurisdictions, creating stronger short-term incentives for emission reductions.[3] Similarly, the Shanghai Municipal Transportation Commission has introduced a dedicated development report within the Shanghai–Los Angeles green shipping corridor initiative. This report systematically maps the deployment pathways of low-carbon vessels and identifies corresponding fuel supply and port infrastructure requirements based on inputs from port authorities and shipping companies.[4] However, the coexistence of global and regional policy frameworks also generates new layers of governance complexity, including potential risks of carbon leakage, regulatory fragmentation, and competitive distortions across different shipping markets (Lyu and Li, 2025).

Taken together, these developments indicate that the evolution of GSCs has progressed from a policy-driven conceptual initiative to a multi-level governance system shaped by interacting technological, economic, and institutional forces. Rather than following a unified pathway, this evolution reflects the increasing entanglement of global ambitions with regionally differentiated implementation approaches, laying the foundation for further examination of how such governance structures influence the operationalization of GSCs.

2.2. Feasibility and bottlenecks in regional corridor developments

Recent years have witnessed a surge in research addressing alternative fuels in the maritime sector (Kian et al., 2026, Wagner, 2025, Solakivi et al., 2022, Gore et al., 2022). Alternative fuels and advanced decarbonization technologies represent the most extensively studied dimension of GSC feasibility research (Liu et al., 2026). Wang and Iris (2025) develop a two-stage stochastic programming model to identify optimal fleet transition pathways under carbon cost uncertainty, evaluating diesel, bio-LNG, bio-methanol, and green ammonia as candidate fuels. Their findings reveal that no single fuel can dominate the future energy landscape: on a well-to-wake basis, bio-methanol emerges as the preferred transition fuel, whereas green ammonia becomes dominant when only tank-to-wake emissions are considered.

At the corridor level, Lyu and Li (2025) compare five alternative fuel options across three regional case studies. It is also worth mentioning that the alternative fuels also have different strengths, weaknesses, opportunities, and threats (Mohammadpour and Salehi, 2025). A consistent finding across these studies is that fuel selection cannot be treated as a universal variable, where the

[1] Link: https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors, Accessed: 9th, April 2026.
[2] Link: https://eur-lex.europa.eu/EN/legal-content/summary/freight-transport-logistics-action-plan.html, Accessed: 9th, April 2026.
[3] Link: https://climate.ec.europa.eu/eu-action/transport-decarbonisation/reducing-emissions-shipping-sector/faq-maritime-transport-eu-emissions-trading-system-ets_en, Accessed: 9th, April 2026.
[4] Link: https://jtw.sh.gov.cn/xydt/20241112/dbefcd4855584f418480c2fb139a058f.html, Accessed: 9th, April 2026.

technically and economically optimal fuel differs substantially depending on route distance, vessel type, and the local bunkering infrastructure already in place (Corcoran et al., 2025). However, recent comparative life cycle and economic analysis confirms that the low-carbon methanol and ammonia can achieve substantial GHG reductions when produced from renewable pathways, positioning them as stronger long-term candidates for maritime decarbonization (Tomos et al., 2024, Ellersdorfer et al., 2026, Chalaris et al., 2025). Zhang and Feng (2024) complement the technical perspective with a tripartite evolutionary game model incorporating government, shipping enterprises, and shippers. Their analysis shows that positive responsiveness from shipping companies requires the simultaneous activation of government subsidies, social financing mechanisms, and a meaningful carbon price signal. Consistently, the study by Ruslan et al. (2025) reinforces this conclusion, demonstrating that while port authorities can derive significant benefits from collaborative strategies, their success is contingent upon government incentives to offset prohibitive initial costs. Furthermore, both studies converge on the premise that for shipping companies, the adoption of low-carbon pathways is a strategic calculation, a delicate balance between incremental operational expenditures and long-term market advantages.

Complementing these strategic analyses, shipping network optimization has emerged as a critical technical tool to address the spatial–temporal mismatch between supply and demand. For example, Wang et al. (2023) proposed a mixed-integer linear program framework to design an Ammonia-based shipping network of alternative fuel production sites, transportation links, and bunkering ports. Wang et al. (2025) developed a nonlinear mixed-integer programming model on Island-land roll-on/roll-off (Ro-Ro) transportation network. Shao et al. (2024) proposed a non-linear programming model jointly optimize green technology adoption, sailing speed, and routing on inland river shipping. As for the GSC, Lyu et al. (2026) formalized the GSC network design problem as a MILP model that simultaneously optimizes route selection, alternative-fuel fleet deployment, and bunkering station placement. However, it should be noted that the integration of advanced digital and intelligent technologies introduces new vulnerabilities to port operations. Hence, strengthening cooperative port security governance is essential within the GSC development discourse (Wang, 2025).

Despite the progress in technical and network modeling, the commercial viability of GSCs remains under-explored from the demand-side perspective. Ellersdorfer et al. (2026) found that the economics of GSCs are not static but are shaped by the dynamic interaction of ship types, corridor characteristics, safety requirements, regulatory overheads, and evolving future scenarios. These complexities further exacerbate the uncertainty of demand-side considerations. Consequently, several ports have launched policy-driven initiatives that enforce environmental regulations while offering compliance incentives. For example, the Port of Rotterdam is at the forefront of this transition, aiming to establish zero-emission GSCs (Dolatabadi et al., 2025). Similarly, Singapore acts as a major participant in GSCs, collaborating with Rotterdam and other hubs to integrate digitalized and sustainable shipping practices (Acciaro et al., 2014).

Research gaps and our contributions

(1) Gap 1: Lack of longitudinal and multi-dimensional analysis between global normative discourse and fragmented regional implementation.

While existing GSC studies provide descriptive accounts of institutional origins, it often treats GSC discourse as a monolithic global agenda. There is a critical lack of study interrogating the structural tensions between the IMO's universalist regulatory norms and the divergent decarbonization trajectories of regional clusters.

Our Contribution: In this study, we constructed a high-fidelity, multi-source GSC corpus spanning the 2021–2025 strategic window. This study constructs a comprehensive GSC corpus that integrates diverse stakeholders, including the IMO, shipping companies, consultancy firms, and regional governmental white papers. By applying NLP techniques, our study moves beyond descriptive policy reviews to quantitatively decode how global normative expectations are contextualized at the regional level, thereby revealing the fragmented nature of global maritime decarbonization.

(2) Gap 2: Lack a sufficient comparative analysis of region-specific bottleneck configurations.

Current GSC studies predominantly adopt a single-region or single-corridor unit of analysis (Dolatabadi et al., 2025), which precludes a systematic understanding of why certain initiatives stagnate while others advance. Furthermore, existing models often relying on generic techno-economic parameters, which tend to obscure the qualitative differences in constraint configurations across diverse trade routes. Consequently, there is a critical lack of a cross-regional comparative lens capable of identifying the heterogeneous barriers that define specific GSCs.

Our Contribution: To address this, our study develops an integrated NLP and Complex Network (CN) framework to visualize and quantify the structural topology of developmental bottlenecks across different regions. By mapping keyword co-occurrence and assessing structural dependencies, this study identifies region-specific thematic priorities and reveals that the binding constraints on GSCs commitment.

(3) Gap 3: Methodological limitations in identifying actionable bottlenecks from unstructured GSC policy corpora.

Existing studies often rely on manual synthesis or expert panels to identify development bottlenecks, which are prone to subjective bias and struggle to handle the sheer volume of global GSC documentation. There is a lack of a rigorous, data-driven approach capable of systematically extracting and aligning high-impact discourse elements with specific implementation barriers across diverse regional big data contexts.

Our Contribution: Advancing GSC policy analysis through Semantic Alignment and Knowledge Mapping. This study develops a systematic method to bridge the gap between large-scale text samples and precise bottleneck identification. Our study isolates high-index score discourse elements to scientifically identify key development bottlenecks. This approach provides a robust empirical foundation for formulating region-specific policy guidance, shifting the research paradigm from subjective interpretation to a reproducible, data-driven framework for GSC strategic planning.

3. Research framework

As shown in Fig. 1, the research framework developed in this study follows a systematic pipeline integrating advanced NLP and CN-based analysis to identify development bottlenecks in GSCs. The framework is structured into four primary steps.

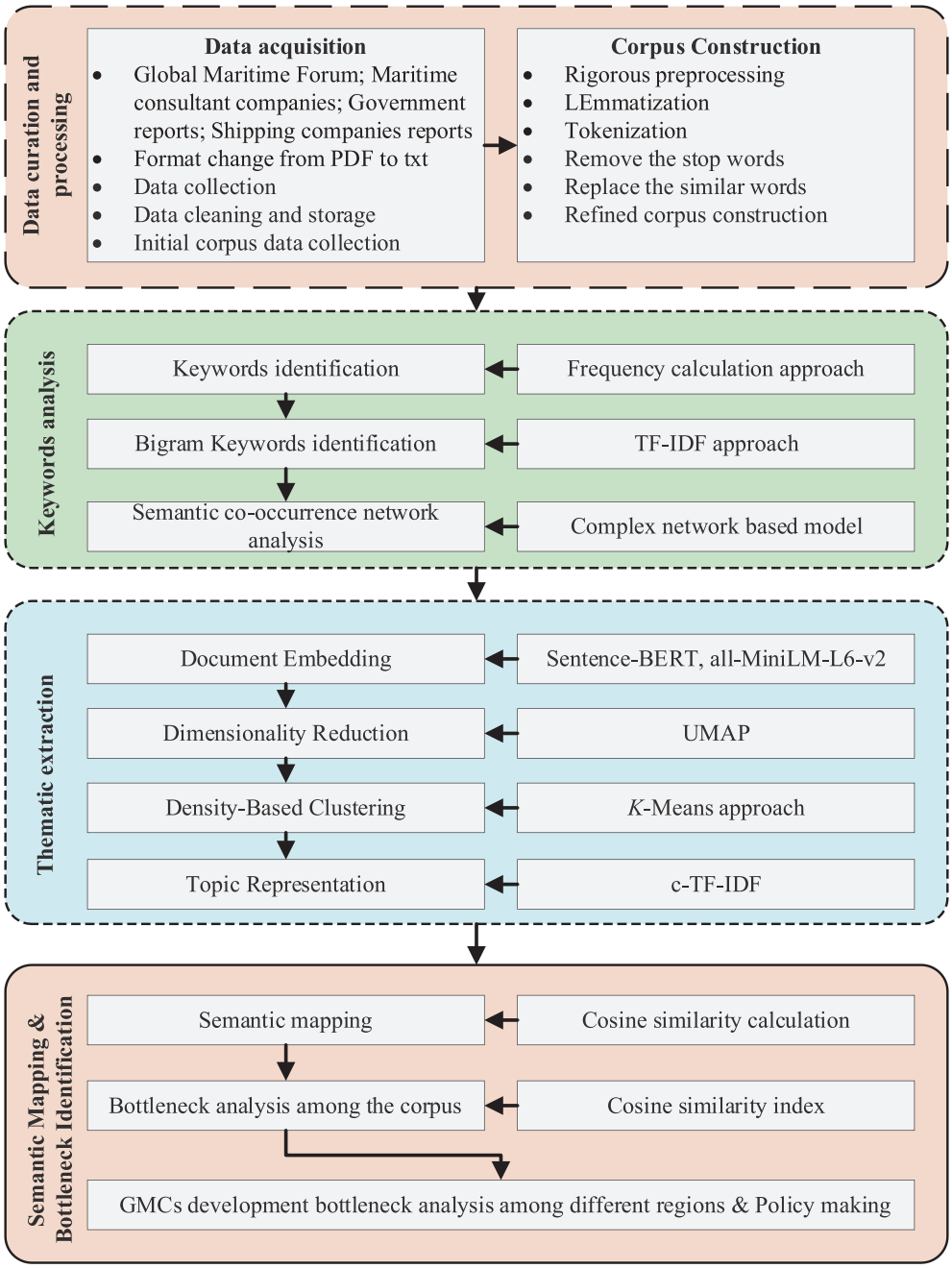


Fig. 1. Research framework design.

Step1: Data Curation and Processing:

A multi-source corpus is constructed from industry reports, government white papers, and Global Maritime Forum (GMF) publications. These sources are specifically selected to reflect real-time policy developments and industry commitments. Academic journal articles are treated separately in the literature review section to provide theoretical grounding, rather than being integrated into the text corpus, in order to avoid conflating conceptual discussions with policy-driven narratives. Then, Rigorous preprocessing, including lemmatization and tokenization, ensures high-quality input for downstream analysis.

Step 2: Keywords Analysis: This step employs frequency calculation and TF-IDF approaches to identifying core terms and bigram keywords. A complex network-based model is then applied to analyze semantic co-occurrence, revealing the structural relationships among different regions.

Step 3: Thematic Extraction: To achieve deep semantic understanding, we utilize a Sentence-BERT model (all-MiniLM-L6-v2) for document embedding, followed by UMAP dimensionality reduction and K-Means clustering. The final topics are represented and interpreted through c-TF-IDF scores index.

Step 4: Semantic Mapping and Bottleneck Identification for results analysis and policy making: By calculating cosine similarity indices, the framework maps semantic gaps across the corpus. This quantitative approach allows for the identification of structural bottlenecks in GSC development across different regions, providing a scientific basis for targeted policy-making and comparing the development bottlenecks among different regions.

3.1. Text preprocessing and statistical keyword identification

A rule-based text preprocessing process is developed to standardize the corpus for subsequent frequency analysis. Raw textual data are first cleaned by removing numerical elements, punctuation, and non-alphabetic characters, followed by normalization to lowercase (Li et al., 2024, Eldeeb and Mohamed, 2022). A combined Stop-word list is constructed by integrating standard English Stop-words with a domain-specific lexicon, excluding generic terms (e.g., “report”, “project”, “industry”) and highly frequent but analytically uninformative research background terms (for example, “maritime” and “shipping”).

The core linguistic processing commences with tokenization, where the cleaned text is segmented using whitespace delimiters followed by a length-based filtering process to remove excessively short tokens. To address morphological variations, a lightweight normalization scheme is applied to focus on common suffix transformations such as the reduction of plural forms to their base roots. The process subsequently generates unigram representations to capture individual semantic units across the corpus. Data aggregation is performed using a counting-based statistical approach to identify the most prominent keywords. The calculation equation is shown below.

$$f(w) = \sum_{i=1}^{N} \Delta(w_i = w) \tag{1}$$

where, $f(w)$ describes the frequency of the keyword w, and $\Delta(\cdot)$ is an indicator function.

3.2. Advanced keyword extraction using TF-IDF and bigram modeling

To identify salient and discriminative semantic patterns with the GSC corpus, the Term Frequency −Inverse Document Frequency (TF-IDF) method is employed. TF-IDF is a widely used statistical measure that evaluates the importance of a term within a document relative to the entire corpus (Li et al., 2024, Aman et al., 2021, Wei et al., 2026). In this study, terms are defined as bigrams constructed from adjacent word pairs, rather than individual words, in order to better capture contextual semantic relationships. Unlike simple frequency counting, TF-IDF balances two components: Term Frequency (TF) is used to measure how frequently a term appears within a given document. And Inverse Document Frequency (IDF), which reflects how unique or informative a term is across the corpus (Wei et al., 2026, Bi et al., 2024).

Formally, the term frequency of a term t within a document d is defined as:

$$TF(t,d) = \frac{f_{t,d}}{\sum_{t' \in d} f_{t',d}} \tag{2}$$

where, $f_{t,d}$ denotes the count of a term t within a document d, and $\sum_{t^* \in d} f_{t^*,d}$ is the total number of term t^* in the document d.

The inverse document frequency is calculated as:

$$IDF(t) = \log\left(\frac{N}{1 + DF(t)}\right) \tag{3}$$

where, N is the total number of documents in the corpus, and $DF(t)$ is the number of documents containing the term t. For a term t across N of corpus D, the DF is given by the following Equation (4):

$$DF(t) = \sum_{d \in D} \partial(t,d) \begin{cases} 1, \text{ if } t \in D \\ 0, \text{ otherwise} \end{cases} \tag{4}$$

where, $\delta(t,d)$ is the function of one term and the document, equals to 1 if the term is present in the document d, and 0 otherwise.

Finally, the TF–IDF score is computed as the product of these two components:

$$TF-IDF(t,d) = TF(t,d) \times IDF(t) \tag{5}$$

In this study, only bigram representations are retained, while unigram terms are excluded to enhance semantic specificity and reduce the dominance of generic expressions. As a result, the TF–IDF framework highlights not only high-frequency patterns but also contextually meaningful phrase-level structures.

3.3. Topological analysis of the semantic co-occurrence network

To further elucidate the structural interdependencies between key terms in the GSC discourse, a weighted undirected co-occurrence network $G = (V, E)$ is constructed. The network is undirected as co-occurrence is inherently symmetric, and edge weights reflect the strength of semantic association between keywords pairs (Zhang et al., 2026). The architecture of the network is defined through the following systematic process. Unlike conventional methods that rely on global frequency, the node set in this study is derived from a multi-stage significance filtering strategy. First, each sub-corpus is analyzed independently to identify its most representative keywords. Secondly, for each sub-corpus, the top Q terms are identified as calculated in Equation (1). And finally, the final candidate node pool V is then formed by the union of these top-ranked common terms.

The edges represent the semantic proximity between the selected keywords. An edge is established between two nodes w_i and w_j if they co-appear within the same analytical paragraph. Paragraph-level co-occurrence is adopted to capture thematic rather than purely syntactic associations, as paragraph boundaries more faithfully reflect coherent units of discourse in the GSC context. The edge weight e_{ij} is defined as the raw co-occurrence frequency of the term pair across the entire corpus. No normalization is applied at this stage, as the primary objective is to reflect the absolute co-occurrence strength rather than relative association; this also preserves comparability across term pairs of varying marginal frequencies. The thickness of edges in the visualization is proportional to e_{ij}, providing an intuitive representation of inter-term association strength.

3.4. Thematic extraction using SBERT and dimensionality reduction

To identify the latent thematic structure of the GSC corpus, this study adopts a hybrid approach by combining TF–IDF-based key term extraction with semantic embedding and clustering techniques (Rath and Chow, 2022, Bhaduri et al., 2026). Specifically, bigram expressions are first extracted using TF–IDF to capture meaningful domain-specific phrases. These textual segments are then transformed into high-dimensional semantic vectors using a Sentence-BERT model, enabling the representation of contextual similarities between terms. Subsequently, a K-means clustering algorithm is applied to group semantically similar expressions into a predefined number of clusters, ensuring interpretability and consistency across analyses (Malaghan et al., 2025). Topic representations are derived using class-based TF–IDF (c-TF-IDF), which aggregates all documents within each cluster into a *meta*-document to identify representative keywords. The overall analytical process consists of four main steps:

Step 1: Document Embedding. To capture deep semantic features, we employed the all-MiniLM-L6-v2 model, a pre-trained Sentence-BERT (SBERT) architecture optimized for English words to encode each document into a dense vector representation (Rath and Chow, 2022). For each document d, SBERT generates a dense vector representation V_d by applying average pooling over the sentence-level embeddings.

$$V_d = \frac{1}{n_s}\sum_{j=1}^{n_s} s_{d,j} \tag{6}$$

where, $s_{d,j}$ represents the embedding vector of the j-th sentence in the document d. n_s represents the total number of sentences contained in the document d.

Step 2: Dimensionality Reduction. Given the high dimensionality of SBERT embeddings, Uniform Manifold Approximation and Projection (UMAP) is applied to project the vectors into a lower-dimensional space (Ghojogh et al., 2023, de Freitas et al., 2025). UMAP is preferred for its ability to preserve both local and global manifold structures. The dimensionality reduction process can be expressed as:

$$f : \mathrm{R}^n \rightarrow \mathrm{R}^m (m \ll n) \tag{7}$$

where the transformation f preserves the topological relationships of the original high-dimensional embeddings in the reduced feature space.

Step 3: Document Clustering. The reduced vectors are clustered using K-Means algorithm (Lloyd, 1982, Arthur and Vassilvitskii, 2007). Following this procedure, each document d is classified to a theme cluster c. The number of clusters is predefined to ensure interpretability and comparability across different analytical settings.

Step 4: Topic Representation (c-TF-IDF). To derive human-readable topic descriptions, we employed c-TF-IDF. This method treats all documents within a cluster as a single *meta*-document to calculate term importance.

$$W_{i,c} = tf_{i,c} \cdot \log\left(1 + \frac{A}{df_i}\right) \tag{8}$$

To establish a structured mapping between cluster-derived topics and theoretically defined bottleneck dimensions, a semantic query framework is developed based on the c-TF-IDF results. Each query is designed as a semantic anchor, integrating three complementary layers: (1) core concepts extracted from the clustering results (e.g., ammonia, hydrogen, investment), (2) functional descriptors grounded in domain knowledge (e.g., bunkering, vessel deployment), and (3) constraint-oriented modifiers (e.g., gap, barrier, uncertainty) to explicitly capture potential bottleneck conditions.

Unlike traditional keyword-based approaches, each query is constructed as a compact semantic representation of a specific structural bottleneck dimension identified from the Section 3.1. To validate the alignment between these semantic queries and the cluster-derived topics, both are encoded into 384-dimensional sentence embeddings using the all-MiniLM-L6-v2 model (Zhao et al., 2026). Cosine similarity is then computed to generate a semantic alignment matrix, providing a quantitative assessment of how well each query corresponds to its intended topic, the calculation Equation is shown as below.

$$CS_{ij} = \frac{\boldsymbol{q}_i \times \boldsymbol{t}_j}{\|\boldsymbol{q}_i\|_2 \|\boldsymbol{t}_j\|_2} = \frac{\sum_{d=1}^{384} q_{id} t_{jd}}{\sqrt{\sum_{d=1}^{384} q_{id}^2} \sqrt{\sum_{d=1}^{384} t_{jd}^2}} \tag{9}$$

where CS_{ij} denotes the cosine similarity between $i-th$ query and the $j-th$ topic; $\boldsymbol{q}_i$ and $\boldsymbol{t}_j$ is used to denote the 384-dimensional embedding vector of the $i-th$ semantic query and $j-th$ cluster-derived topic, respectively. q_{id} is the $d-th$ dimension of vector $\boldsymbol{q}_i$; t_{jd} denotes the $d-th$ dimension of vector $\boldsymbol{t}_j$.

4. Empirical analysis and results

This section presents the empirical findings of the study, transitioning from the theoretical framework to a data-driven investigation of GSCs development bottlenecks among different regions. By leveraging a multi-source corpus, the analysis aims to decode the complex evolution of green maritime transition through the lens of lexical semantics and structural network mechanisms. The following sections detail the data processing pipeline, the identification of thematic shifts, and the quantitative results of semantic alignment across different maritime stakeholders.

4.1. Data acquisition and pre-processing

To ensure both source diversity and analytical representativeness, the corpus was constructed through systematic collection of GSC development reports from three categories of institutional sources, including the government agencies and intergovernmental bodies, maritime research and analytical organizations, and industry-led commercial entities. This multi-source sampling strategy was designed to capture the full spectrum of perspectives shaping GSC discourse, ranging from top-down regulatory frameworks to bottom-up operational assessments. The detailed data are organized as Table 1.

Following the automated preprocessing pipeline, all candidate documents underwent manual review to assess their analytical suitability for inclusion in the final corpus. This screening process evaluated each report against two criteria: informational density and linguistic accessibility. Documents with insufficient substantive content, such as those consisting primarily of executive summaries, graphical presentations, or tabular data with limited accompanying analytical text, were excluded on the grounds that they would contribute disproportionately low signal relative to noise in subsequent frequency-based and semantic analyses. Hence, the documents 13 to 16 are deleted from the corps construction. Additionally, reports published in languages other than English were excluded to

Table 1
Summary of Key Reports and Feasibility Studies on GSCs.

No.	Report	Region	Year	Organization
1	Asia–Pacific Green Shipping Corridor	Asia–Pacific	2023	ESCAP
2	Western Australia – East Asia Green Shipping Corridor	Oceania–Asia	2024	GMF
3	Green Shipping Corridors and Partnerships	Oceania	2024	Australian Government
4	South Africa – Europe Green Shipping Corridor	Africa–Europe	2024	GMF
5	Spain Green Corridor Initiative	Europe	2023	GMF
6	Canadian Green Shipping Corridors Framework	North America	2025	Government of Canada
7	US Green Shipping Corridors Framework	North America	2022	US Government
8	Green Shipping Corridors and Partnerships	Europe	2024	Norwegian Ministry of Climate and Environment
9	Chilean Green Corridors	South America	2025	Mærsk Mc-Kinney Møller Center
10	Port of Los Angeles – Port of Shanghai Green Shipping Corridor Partnership Implementation Plan Outline	North America–Asia	2025	C40
11	Europe-Asia Green CorridorsCase for Morocco as a green shipping H2 hub	Europe–Asia	2024	Transport & Environment
12	Green Shipping Corridors annual reports	Global	2021–2025	GMF
13	Australia Green Shipping Corridor Policy	Oceania	2023	ARUP
14	US Maritime Fleet Decarbonization Outlook	North America	2022	UMAS
15	Singapore–Australia Green and Digital Shipping Corridor	Asia–Oceania	2024	Governments of Singapore and Australia
16	Singapore–China Green and Digital Shipping Corridor	Asia	2024	Governments of Singapore and China

ensure linguistic consistency across the corpus and to maintain the validity of the NLP-based analytical procedures applied in this study.

It is also noteworthy that although the publication years of the selected documents are not fully consistent, their integration into a unified corpus is appropriate for the purpose of this study. The main reasons are threefold. Firstly, most GSC initiatives remain in the early-start stages and the available documents primarily discuss the structural implementation bottlenecks rather than evaluating mature performance outcomes. Second, the regional analysis aims to identify structural similarities and differences in documented bottlenecks instead of conducting a year-by-year longitudinal analysis. Finally, the reports were combined to develop corpus, the publication years and the sources are not incorporated as textual features. In contrast, the annual GMF reports were analysed separately to identify the changes in global GSC initiatives over time. Accordingly, the regional results should be interpreted as a comparative mapping of the available regional discourse rather than as a strictly longitudinal compassion.

To enable systematic regional comparison, the retained documents were subsequently classified into three regional corpora based on the geographic coverage of the corridors addressed in each report. While a more granular geographic classification was initially considered, preliminary assessment indicated that finer-grained regional subdivisions would result in corpus sizes insufficient to support reliable thematic clustering and semantic alignment analysis. Accordingly, the remained reports were consolidated into three regional groupings, the detailed aggregated region and classification are organized as shown in Table 2. This three-region classification balances geographic specificity with corpus adequacy, ensuring that each regional sub-corpus contains sufficient textual content to support robust downstream analysis. Finally, the document 12 are used to reflect the global GSCs development and used as the baseline for comparing the difference among the regions.

Table 3 presents the descriptive statistics of paragraph length across the four analytical corpora. The final corpus comprises 1,445 paragraphs in total, with the Global Reports corpus contributing the largest share (652 paragraphs), followed by the Trans-Atlantic and European corpus (450 paragraphs), the Asia-Pacific corpus (250 paragraphs), and the Trans-regional Long-distance Corridors corpus (93 paragraphs). The relatively smaller size of the Trans-regional corpus reflects the more limited availability of publicly accessible reports dedicated exclusively to intercontinental long-haul corridor development, which further justifies the decision to treat this category as a consolidated analytical unit rather than subdividing it into finer geographic segments.

In terms of paragraph length, the Asia-Pacific, Trans-Atlantic and European, and Trans-regional corpora exhibit broadly comparable mean word counts, ranging from 104.5 to 108.4 words per paragraph, with standard deviations between 20.5 and 24.5, indicating relatively consistent informational density across these three regional corpora. In contrast, the Global Reports corpus displays a notably lower mean word count of 74.5 words per paragraph, suggesting that globally-oriented reports tend toward more concise and declaratory paragraph structures, consistent with the agenda-setting and policy coordination functions identified in the discourse analysis presented in Section 4.1. These distributional characteristics were taken into account during the subsequent analytical procedures to ensure that cross-corpus comparisons remain interpretively valid.

4.2. Convergent and divergent evolution of green shipping from lexical semantics to network mechanisms

4.2.1. Lexical landscape analysis and comparative study of global and regional corpora

Based on the calculations using Equation (1), the top 30 terms are identified using the statistical keyword identification approach described in Section 3.1. The lexical comparison across the four corpora reveals both similarity and differentiation in the discourse on GSCs. As shown in Fig. 2, across all corpora, terms such as *ammonia*, *hydrogen*, *production*, and *energy* appear frequently, indicating a shared concern with the deployment of zero-emission fuels, the establishment of supporting supply infrastructure systems, and the formation of shipping market-based demand generation. This suggests that, regardless of scale, discussions on GSCs are consistently centered on alternative fuel pathways, supply readiness, operational deployment, and stakeholder investments decisions.

Despite these commonalities, the global corpus differs markedly from the three regional corpora in its lexical emphasis. Fig. 3 presents only the top 10 key terms from each of the four corpora to maintain conciseness and visual clarity. In the global reports, high-frequency terms such as *initiative*, *ammonia*, *policy*, *government*, *stakeholder*, and *progress* are particularly salient. This pattern suggests that the global discourse is framed primarily around agenda setting, governance coordination, and the staged commercial advancement of GSCs. In other words, the global corpus places are trying to understand the complex relationships on the development of GSCs and stronger emphasis on how green corridors should be initiated, governed, coordinated, and scaled over time.

Table 2
Aggregated Region and Classification Description.

Region	Original Labels	Description	No.
Asia-Pacific	Asia, Asia–Pacific, Oceania, Oceania–Asia, Asia–Oceania	Encompasses intra-Asian corridors and closely integrated maritime linkages between Asia and Oceania, reflecting shared trade structures and fuel transition dynamics centered on bulk commodity flows.	1–3
Trans-Atlantic and European	Europe, North America, Africa–Europe	Captures corridors operating within and adjacent to the North Atlantic basin, characterized by shared regulatory frameworks including the EU MRV regulation and comparable policy maturity levels across participating jurisdictions.	4–8
Trans-regional Long-distance Corridors	North America–Asia, Europe–Asia, South America	Covers long-haul intercontinental trade routes spanning multiple regulatory jurisdictions, typically involving more complex cross-border governance arrangements, greater fuel supply chain uncertainty, and higher techno-economic feasibility thresholds.	9–11

Table 3
Descriptive Statistics of Paragraph Length among four Corpora.

Corpus	Number of Paragraph	Mean of words	S.D. of words
Asia-Pacific	250	104.5	20.5
Trans-Atlantic and European	450	108.3	24.5
Trans-regional Long-distance Corridors	93	108.4	23.8
Global reports	652	74.5	20.3

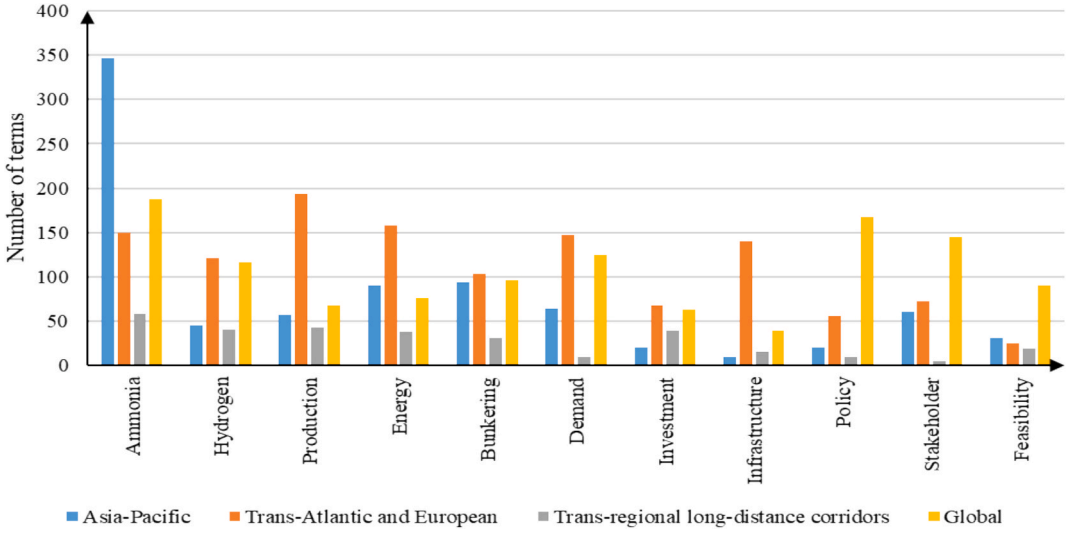


Fig. 2. Comparative analysis of key common terms frequencies across four corpora.

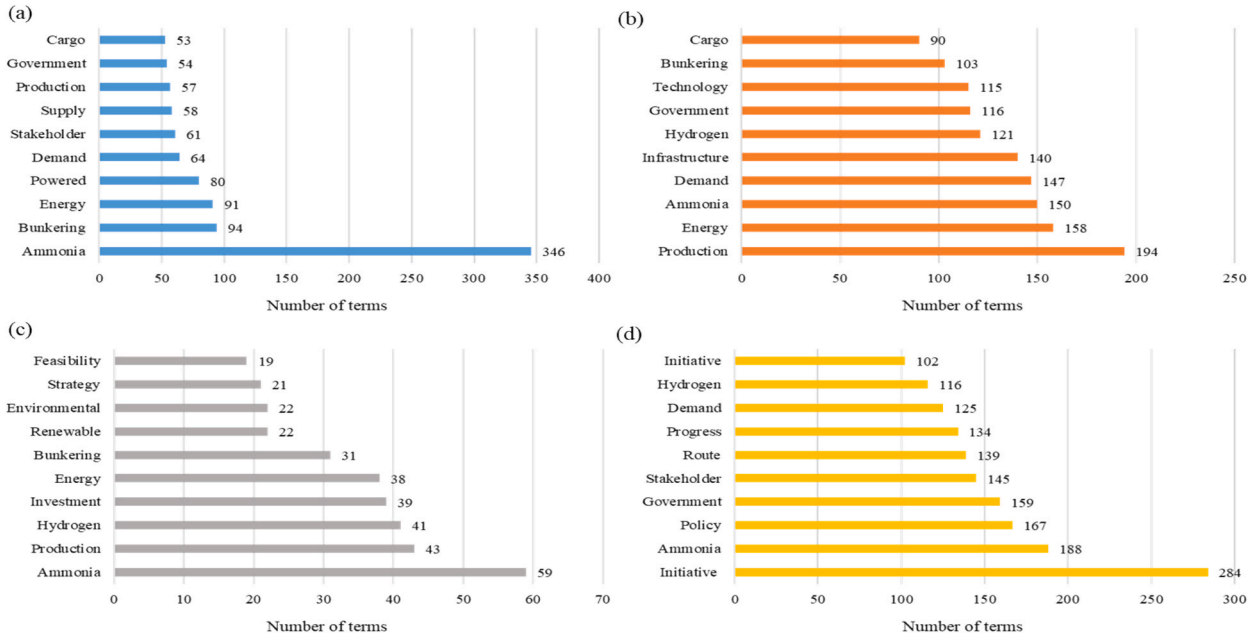


Fig. 3. Top 10 terms and frequencies across the four corpora: (a) Asia-Pacific; (b) Trans-Atlantic and European; (c) Trans-regional long-distance corridors; (d) Global analysis.

In contrast, the regional corpora underscore more empirical constraints and opportunities associated with practical implementation. Specifically, the Asia-Pacific corpus is characterized by terms such as *ammonia*, *bunkering*, *powered*, *partnership*, *carrier*, *route*, *safety*, *agreement*, and *service*. These lexical patterns point to a route-level implementation logic in which the main concerns relate to fuel deployment, vessel operations, cross-value-chain partnerships, and safety or design considerations. The prominence of terms such as *carrier*, *service*, and *route* also indicates a relatively strong operational orientation in this regional discourse.

The Trans-Atlantic and European corpus displays a different lexical profile. Alongside *production*, *energy*, *ammonia*, and *demand*, terms such as *infrastructure*, *technology*, *battery*, and *ferry* are highly ranked. This suggests a broader systems-transition perspective, where maritime decarbonization is discussed not only in terms of fuel deployment but also through the interaction of infrastructure readiness, technological pathways, domestic or short-sea applications, and market formation. Compared with the Asia-Pacific corpus, this corpus places greater emphasis on the enabling conditions required to integrate GSCs into wider transport and energy integrated systems.

The *trans*-regional long-distance corridor corpus presents yet another distinct pattern. In addition to *ammonia*, *production*, and *hydrogen*, frequent terms include *investment*, *renewable*, *regulatory*, and *electricity*. This lexical structure points to a supply-side feasibility logic centered on fuel production capacity, renewable electricity availability, investment conditions, and regulatory support. The prominence of *autonomy* further suggests that long-distance operational requirements remain an important concern in this category of corridor policy support. Overall, this corpus is less focused on immediate coordination or route management and more focused on whether the upstream energy and investment conditions are sufficient to support long-distance corridor development.

Taken together, these findings indicate that while GSCs are globally framed as collaborative transition initiatives, regional and corridor-specific documents reveal more differentiated bottlenecks. The Asia-Pacific discourse is more strongly associated with route implementation and operational coordination. The Trans-Atlantic and European discourse is more closely linked to infrastructure,

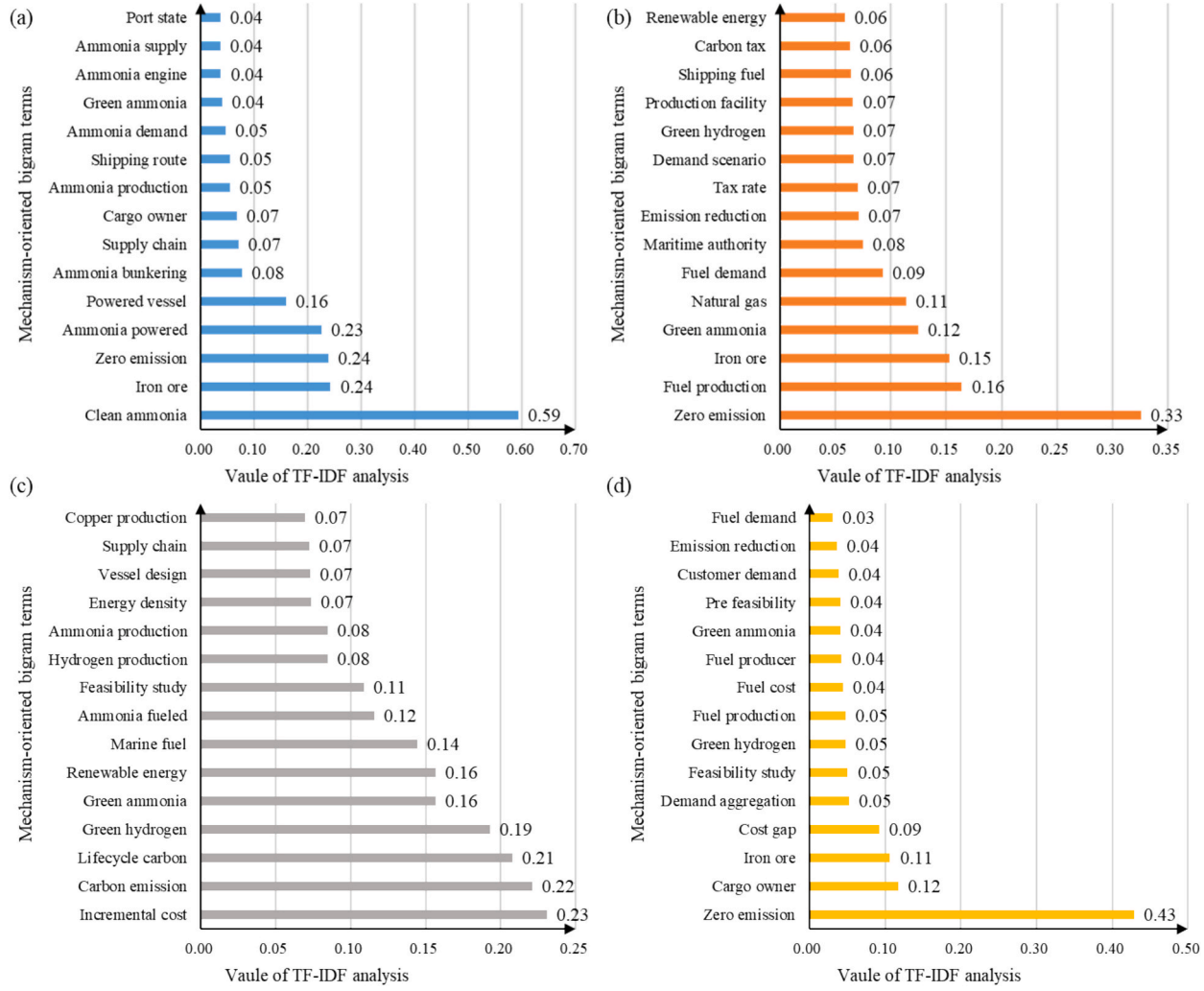


Fig. 4. Mechanism-oriented bigram analysis and TF-IDF values across the four corpora: (a) Asia-Pacific; (b) Trans-Atlantic and European; (c) Trans-regional long-distance corridors; (d) Global analysis.

technology, and market formation. The *trans*-regional long-distance discourse is more heavily shaped by fuel production, renewable resource availability, and investment-regulatory feasibility. These differences suggest that GSCs should not be understood as a uniform global policy object; rather, their practical development is shaped by distinct regional and functional governance logics.

4.2.2. *Thematic bigram analysis for unveiling regional divergence in functional mechanisms*

Then, the TF–IDF approach described in Section 3.2 is employed to identify thematic bigrams across four different corpora. The results are shown in Fig. 4, the bigram analysis reveals clear differentiation between the global corpus and the three regional corpora.

While the global corpus is dominated by broad transition-related expressions such as cost gap, demand aggregation, feasibility study, fuel production, fuel cost, and customer demand, the regional corpora exhibit more specific implementation logics shaped by corridor type, fuel pathway, and infrastructure conditions. This contrast suggests that the global discourse primarily frames the transition challenge in terms of coordination, commercial viability, and generalized deployment feasibility, whereas regional corpora are more strongly anchored in concrete operational and techno-economic constraints.

In the Asia-Pacific region, the most salient bigrams include clean ammonia, iron ore, zero emission, and ammonia powered. These terms indicate a corridor logic closely tied to bulk commodity transport and vessel-specific fuel substitution. Rather than emphasizing broad governance narratives, this regional corpus is structured around the practical deployment of ammonia in established shipping routes, especially those associated with resource transport. The simultaneous prominence of ammonia powered, ammonia engine, and ammonia bunkering suggests that the discourse is concentrated on shipboard application, fuel availability, and supporting logistics, while iron ore points to the importance of commodity-linked trade structures in shaping corridor development. Overall, Asia-Pacific region highlights the huge potential on the Ammonia as the alternative fuel for GSCs realization.

In Trans-Atlantic and European region, the dominant bigrams include fuel production, green ammonia, natural gas, and fuel

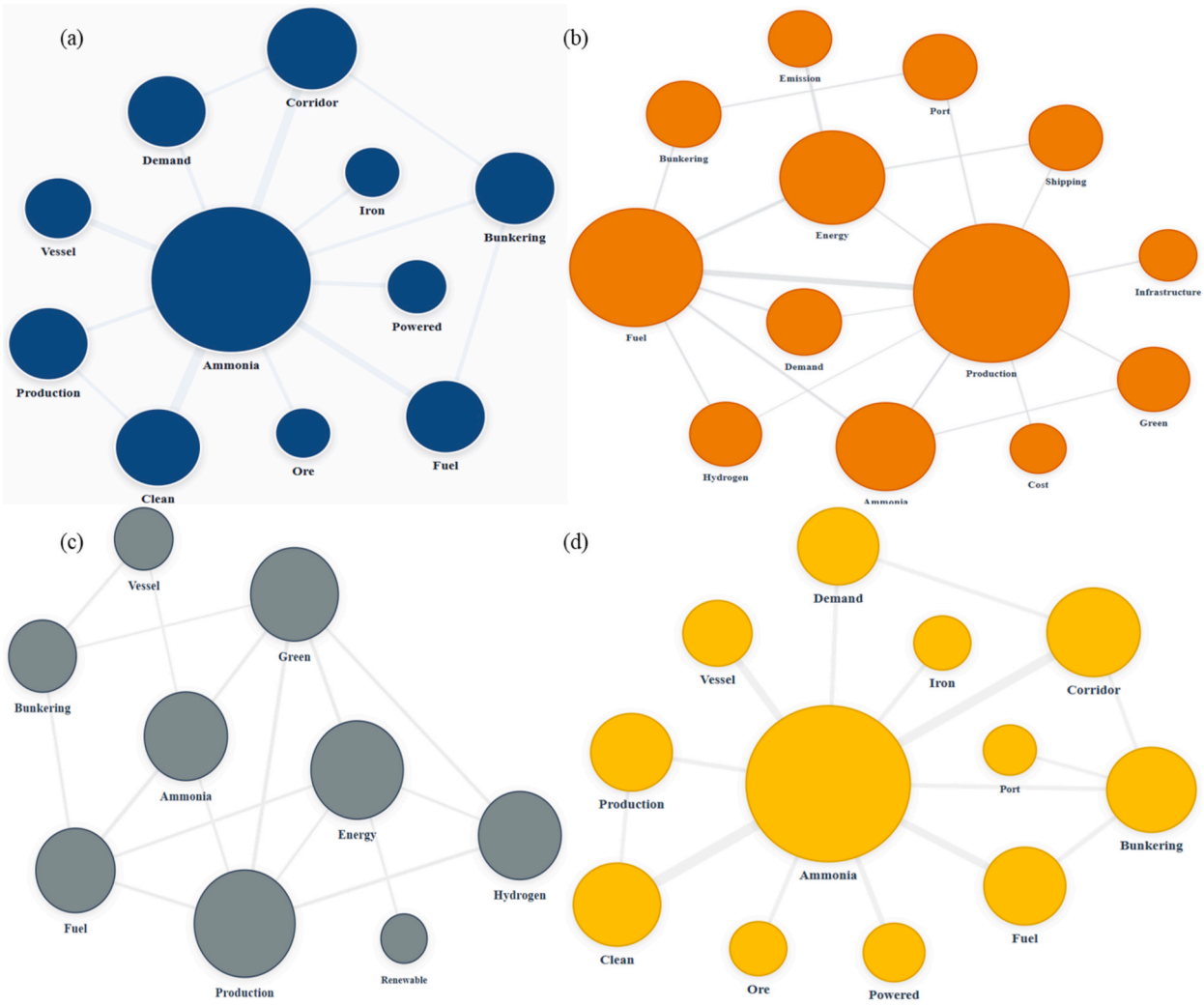


Fig. 5. Keyword co-occurrence networks of GSCs corpora across different regional dimensions. (a) Asia-Pacific region, (b) Trans-Atlantic and European region, (c) interregional long-distance corridors, and (d) global-level discourse.

demand. Compared with Asia-Pacific region, this corpus places greater emphasis on upstream production capacity, policy instruments, and supply-side investment conditions. At the same time, terms such as carbon tax, carbon sequestration, and energy efficiency show that the regional discourse is not limited to fuel switching itself, but also engages with broader decarbonization economics and mitigation strategies. The appearance of demand scenario further suggests that implementation uncertainty is discussed in relation to future market uptake and scale formation. Taken together, Trans-Atlantic and European region represents a supply-oriented transition logic in which production feasibility, infrastructure build-out, and policy-mediated cost conditions are central bottlenecks.

As for *trans*-regional long-distance corridors, the key bigrams are incremental cost, carbon emission, lifecycle carbon, green hydrogen, and green ammonia. This corpus is distinguished by a strong focus on comparative techno-economic assessment and life-cycle evaluation. Terms such as incremental cost, carbon emission, and lifecycle carbon indicate that the transition challenge is framed not only in terms of fuel availability, but also in terms of emissions accounting, economic burden, and full-chain performance evaluation. Compared with the more route-embedded logic in Asia-Pacific region and the production-oriented logic in Trans-Atlantic and European region, *trans*-regional long-distance corridors foregrounds the analytical assessment of fuel alternatives, especially their lifecycle performance and operational viability across longer and more complex transport systems. This suggests a transition logic shaped by evaluation complexity, technology comparison, and full-chain feasibility rather than by a single dominant deployment bottleneck.

The global corpus presents a markedly different pattern. Its dominant bigrams, including cargo owner, cost gap, demand aggregation, and feasibility study, suggest a discourse that remains largely positioned at the level of strategic coordination and transition framing. Compared with the regional corpora, the global corpus gives stronger prominence to generalized commercial barriers and enabling conditions, especially the mismatch between fuel cost and customer willingness to pay, as reflected in cost gap, fuel cost, and customer demand. However, this framing is less specific in terms of localized implementation conditions than the regional corpora. In other words, the global discourse identifies the main categories of challenge, but the regional corpora reveal how these challenges materialize through distinct corridor-specific mechanisms.

Taken together, these findings confirm that the discourse on GSCs is not structured around a single universal implementation pathway. Instead, the global narrative emphasizes commercial feasibility, demand coordination, and broad transition momentum, whereas regional corpora reveal differentiated bottleneck configurations. Asia-Pacific region is dominated by route-embedded ammonia deployment and vessel application; Trans-Atlantic and European region by fuel production, supply demand, and policy-conditioned scale formation; and *trans*-regional long-distance corridors by lifecycle assessment, incremental cost, and comparative fuel feasibility. This divergence supports the argument that the current global agenda tends to frame corridor development in generalized strategic terms, while actual implementation is governed by regionally specific techno-economic and infrastructural constraints.

4.2.3. Relational network analysis of global landscapes and regional heterogeneity in co-occurrence patterns

This study utilizes keyword co-occurrence networks to decipher the evolving logic of GSCs across multiple dimensions. Based on the key common terms identification results collected from the Section 4.1, the detailed keyword extraction and frequency calculations are compiled. As shown in Fig. 5, The visualizations presented based on the Top 20 keywords ranked by co-occurrence frequency within each dimension. Based on the results, we observe that global maritime decarbonization has transitioned from early conceptual discussions to a differentiated implementation phase driven by regional resource endowments and policy influence.

In the Asia-Pacific region, the co-occurrence network exhibits a distinctive ammonia-based driven symbiotic character. Our result reveals an intense correlation between Ammonia and Clean (83) and Corridor (75), suggesting that ammonia is viewed not merely as a zero-carbon alternative fuel but as the primary vehicle for corridor realization in this region. Diverging from the European region, the decarbonization logic in the Asia-Pacific is heavily dictated by industrial demand. The co-occurrence of Ammonia and Iron/Ore (31) reflects a deep integration between green corridor development and the dry bulk trade flows between Australia and East Asia. Furthermore, the frequent associations of Ammonia with Powered (40) and Vessel (57) underscore the region's leading position in the engineering and propulsion systems required for ammonia-fueled shipping.

In contrast, the Trans-Atlantic and European region demonstrates a network structure centered on infrastructure maturity and a multi-fuel policy logic. The core of this network is anchored by Production and Fuel (103), reflecting Europe's strategic focus on the upstream energy supply side. Unlike the singular technological preference seen in the Asia-Pacific region, Europe maintains a balanced interest across Ammonia (60) and Hydrogen (51). The high-frequency co-occurrence of Energy and Emission (64), along with Production and Infrastructure (50), reveals that under the stringent regulatory framework of the European Union, the region is securing its energy transition through the construction of advanced infrastructure across ports, which evidenced by the 47 correlations between Bunkering and Port. This indicates that Europe has moved beyond technological debate and entered an execution phase defined by infrastructural guarantees and systemic regulation.

In the dimension of Trans-regional long-distance corridors, the network density is relatively lower but highly thematic. This sub-network functions as a green energy bridge connecting energy-exporting hubs with consumption centers. The primary anchors are Production-Green (21) and Energy-Green (20). These nodes emphasize that the paramount task for long-haul corridors is verifying the legitimacy and sustainability of cross-border renewable energy. However, the emergence of Bunkering-Vessel (17) and Ammonia-Vessel (12) reflects the technical bottlenecks faced in long-distance operations. These challenges specifically involve mid-voyage refueling, long-range fuel storage, and vessel seaworthiness. This suggests that the essence of *trans*-regional collaboration lies in balancing the geographical disparity of energy resources with techno-economic feasibility.

Lastly, the global synthesis serves as the policy engine and systemic coordinator. It harmonizes fragmented regional efforts into a unified global consensus. Policy-Corridor (77) and Policy-Fuel (73) emerge as the highest-order constraints. These factors establish the

dominance of global regulatory frameworks in governing the mosaic of corridors. As the weights of terms like Feasibility-Corridor (55) and Policy-Cost (46) increase, the global narrative undergoes a critical shift. The focus is moving from technological possibility to economic bankability. Simultaneously, the high correlation between Demand-Fuel (72) and Demand-Corridor (68) sends a clear signal to the market. De-risking investments through off-take agreements has become the decisive step in moving green shipping corridors from blueprint to reality.

In summary, the evolution of GSCs is no longer a singular global movement but a "tri-polar" decarbonization logic. The Asia-Pacific relies on specific industrial verticals for point-to-point breakthroughs; Europe establishes systemic advantages through infrastructural and regulatory maturity; and the global level provides the scaffolding through policy coordination and economic frameworks. This synergy, grounded in regional heterogeneity, is actively shaping the future landscape of deep decarbonization in the global maritime industry.

4.3. *Theme exaction and distribution analysis*

Based on keywords identification outputs from Section 4.1 and domain knowledge from our authors, four potential themes are set for theme extract and analysis, corresponding to key dimensions of GSC development: alternative fuel pathways, infrastructure and operational deployment, demand and commercial viability, and institutional and governance mechanisms. Hence, the value of *K*-means algorithm is set as four to identifying the core themes construction.

The clustering results based on the c-TF-IDF method reveal a structured and multi-dimensional representation of bottlenecks in GSC development. Rather than forming isolated thematic groups, the extracted clusters collectively reflect a layered transition process, where constraints evolve from early-stage institutional formation to large-scale economic implementation challenges. These clusters jointly illustrate that GSC development is not constrained by a single factor, but rather by interdependent bottlenecks across multiple stages of system transition. The details core keywords and the corresponding TF-IDF values are shown in Fig. 6. Additionally, the detailed themes are organized as below.

(1) System-level Economic and Scalability Barriers

This theme captures the macro-level economic and scalability constraints of GSC development. High-weight terms such as cost, demand, production, and investment indicate that large-scale implementation is primarily hindered by economic feasibility and sustainability of the associated supply chains.

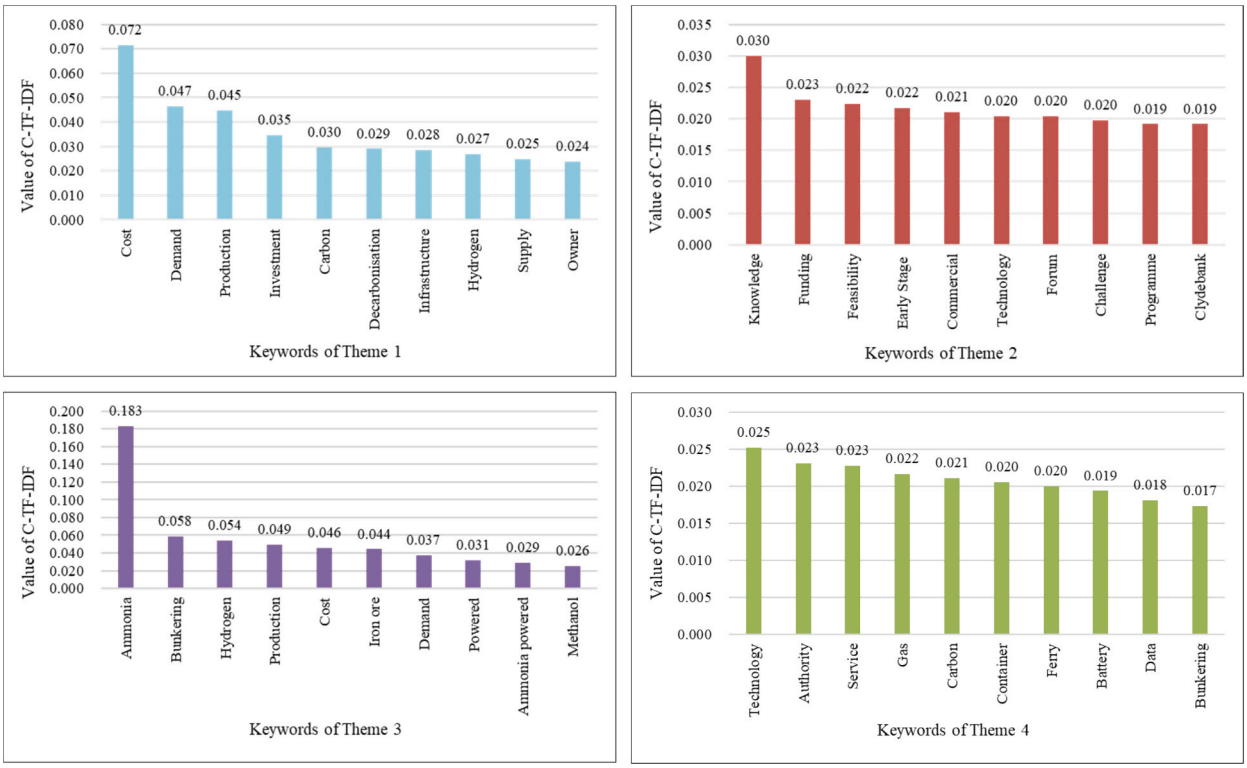


Fig. 6. Core keywords and corresponding C-TF-IDF values for four themes.

(2) Institutional and Early-stage Governance Constraints

The second theme cluster captures the institutional and early-stage governance dimension of GSC development. Key terms such as knowledge, funding, feasibility, and programme indicate that initial corridor development is primarily constrained by limited knowledge accumulation, financing uncertainty, and feasibility assessment challenges. The presence of policy-related terms such as Clydebank and forum further suggests that early-stage progress is strongly driven by international policy initiatives and collaborative platforms, rather than market-based mechanisms. This highlights that GSC development in its initial phase relies heavily on institutional mobilization and stakeholder coordination, forming the foundation for subsequent implementation.

(3) Fuel Pathway and Technological Transition Dynamics

The third cluster reflects the fuel pathway and technological transition dimension, characterized by dominant terms such as ammonia, hydrogen, methanol, and bunkering. These results indicate that decarbonization strategies in GSCs are closely linked to alternative fuel adoption and infrastructure readiness.

(4) Operational and Sector-specific Deployment Challenges

The last cluster represents the operational and sector-specific implementation layer, with key terms including container, ferry, battery, and service. This indicates that different shipping segments adopt distinct decarbonization strategies, reflecting variations in operational requirements and technological maturity. The inclusion of terms such as technology, data, and authority suggests that effective implementation depends on digital integration, regulatory support, and coordinated governance mechanisms. This cluster highlights that, beyond technological feasibility, the success of GSCs relies on operational alignment across multiple stakeholders and system components.

Fig. 7 presents the distribution of thematic clusters across regions, revealing substantial structural heterogeneity in the development of GSCs.

At the global level, the discourse is predominantly shaped by system-level economic and institutional considerations, with Theme 1 (39.17%) and Theme 2 (27.96%) accounting for the largest proportions. This indicates that global reports primarily emphasize economic feasibility, investment scalability, policy support, and institutional mobilization as prerequisite conditions for corridor development. In contrast, regional corpora demonstrate a clear shift toward implementation-oriented themes, particularly alternative fuel pathway identification and operational deployment. This divergence suggests that while global narratives focus on agenda setting and enabling frameworks, regional practices are more closely aligned with technological realization and operational execution. Such a contrast reflects a structural mismatch between globally framed priorities and regionally grounded implementation challenges.

Specifically, the Asia-Pacific region is characterized by a strong concentration in Theme 3 (54.62%), with comparatively limited emphasis on economic and institutional dimensions. This distribution reflects a development pathway that is primarily driven by fuel

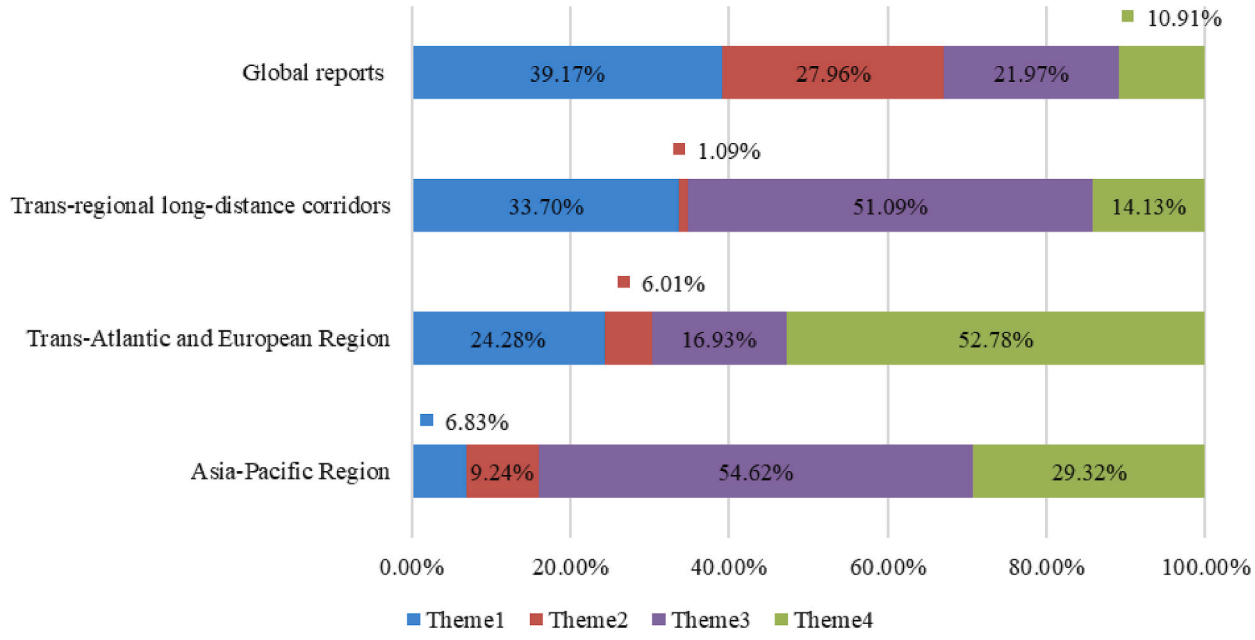


Fig. 7. Distribution of thematic clusters across four corpora: (a) Asia-Pacific; (b) Trans-Atlantic and European; (c) Trans-regional long-distance corridors; (d) Global analysis.

transition and technological implementation. This region places greater emphasis on alternative fuel availability, bunkering infrastructure, and corridor-level operational feasibility. The prominence of terms associated with ammonia, hydrogen, and methanol further indicates that decarbonization efforts are closely linked to supply-side energy transitions rather than early-stage governance formation. Consequently, GSC development in the Asia-Pacific region can be understood as an implementation-driven process, in which technological readiness and fuel pathway realization play a central role in shaping transition dynamics.

In contrast, the Trans-Atlantic and European region exhibits a markedly different thematic structure, with a dominant contribution from Theme 4 (52.78%) and a substantial presence of Theme 1 (24.28%). This pattern suggests a governance–infrastructure coupled transition pathway, in which operational deployment is strongly supported by established institutional frameworks and regulatory mechanisms. The relatively high proportion of operational themes indicates that the region has progressed beyond early-stage feasibility concerns and is actively advancing system-level implementation. This progression is closely associated with mature policy instruments, coordinated infrastructure investments, and market-based mechanisms that collectively facilitate decarbonization. As a result, GSC development in this region reflects a policy-driven system transition logic, where institutional arrangements actively enable and accelerate operational scaling.

A particularly notable finding emerges in *trans*-regional long-distance corridors, where Theme 2 accounts for only 1.087%, representing a significantly lower proportion than observed in other regions. Rather than indicating the absence of institutional considerations, this pattern suggests a different development trajectory in which the conventional early-stage governance phase is effectively compressed or bypassed. This phenomenon can be attributed to the presence of pre-established international frameworks, such as the Clydebank Declaration and other governmental initiatives, which provide prior policy alignment and stakeholder coordination at the global level. In addition, flagship corridors, such as the cooperation between the Port of Los Angeles and the Port of Shanghai, have already established formalized collaboration frameworks and pilot initiatives at an early stage. These arrangements enable corridor development to move rapidly toward fuel pathway optimization and economic feasibility considerations, thereby reducing the relative prominence of institutional constraints in regional discourse. As a result, *trans*-regional corridors exhibit a development pattern that transitions directly from global coordination to technological and economic challenges.

Taken together, these findings demonstrate that GSC development does not follow a uniform or linear development pathway, but instead reflects differentiated governance logics across spatial scales. Global-level discourse is primarily oriented toward agenda setting and institutional mobilization, whereas regional development trajectories are shaped by distinct implementation priorities. The Asia-Pacific region follows a fuel-driven and implementation-oriented pathway, the Trans-Atlantic and European region reflects a policy-enabled system transition, and *trans*-regional corridors exhibit a pre-conditioned and fast-tracked development pattern. These differences highlight that the transition toward maritime decarbonization is inherently heterogeneous, with regional variations driven by institutional maturity, economic structure, and strategic positioning within global supply chains.

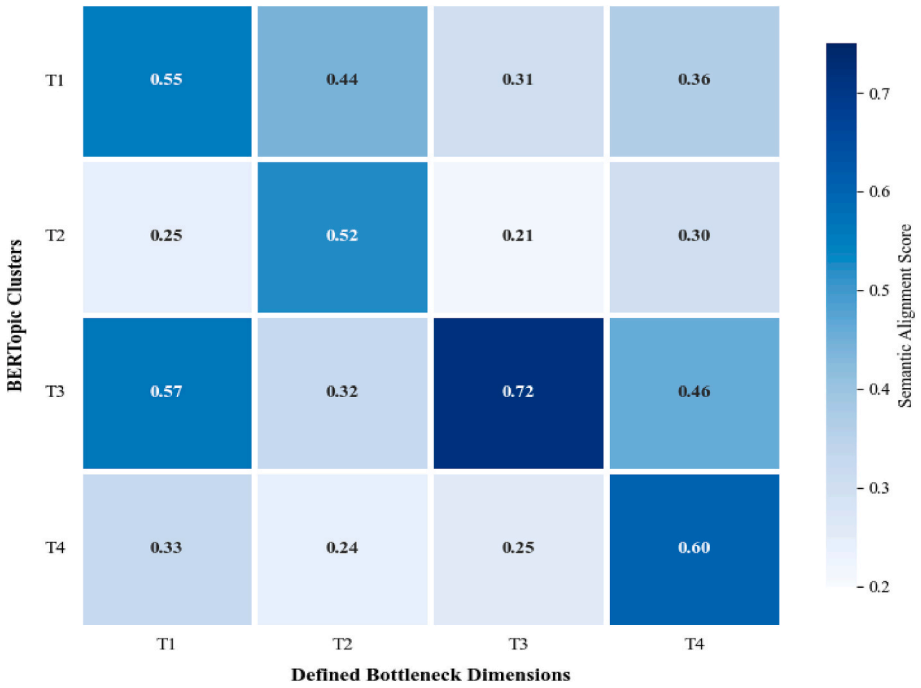


Fig. 8. Semantic Alignment Between BERTopic Clusters and Defined Bottleneck Dimensions.

4.4. Semantic alignment and knowledge mapping

4.4.1. Semantic alignment results

As shown in Fig. 8, the semantic alignment matrix exhibits a clear diagonal dominance pattern, indicating that each query anchor achieves its highest similarity with the corresponding cluster-derived topic.

In particular, the fuel pathway and technological transition dimension (T3) exhibits the highest alignment score (0.72), suggesting that this theme is the most coherently captured within the corpus. Similarly, the operational and sector-specific deployment challenges (T4) and the system-level economic and scalability barriers (T1) demonstrate strong alignment (0.60 and 0.55, respectively), while the institutional and early-stage governance constraints (T2) also show a consistent, albeit slightly lower, alignment (0.52). These results confirm that the semantic anchor design effectively captures the core thematic structure of GSC development. This confirms the robustness of the semantic query design and its consistency with the underlying thematic structure identified by the clustering model proposed from Section 3.4.

Beyond the dominant diagonal structure, the presence of moderate off-diagonal correlations reveals meaningful interdependencies among bottleneck dimensions. For instance, a relatively high cross-alignment is observed between the fuel pathway dimension (T3) and the system-level economic constraints (T1) (0.57), indicating that alternative fuel transitions are closely intertwined with economic feasibility and large-scale production constraints. This finding reinforces the notion that technological transitions in GSCs cannot be decoupled from cost structures and supply-side scalability.

Taken together, these findings highlight that GSC bottlenecks are not isolated but form a structurally interdependent system. While each dimension maintains clear semantic distinctiveness, the observed cross-dimensional linkages reflect the complex socio-technical nature of corridor development. In particular, the strong coupling between fuel pathways and economic scalability underscores that resolving the "green premium" remains central to unlocking large-scale deployment, whereas institutional coordination serves as an enabling foundation for both technological transition and operational implementation. This integrated perspective provides a more realistic representation of GSC development challenges and supports the use of a multi-dimensional analytical framework.

4.4.2. Structural bottlenecks identification across corpora

As shown in Fig. 9, the distribution of structural bottlenecks exhibits substantial variation among the four analytical contexts: (a)

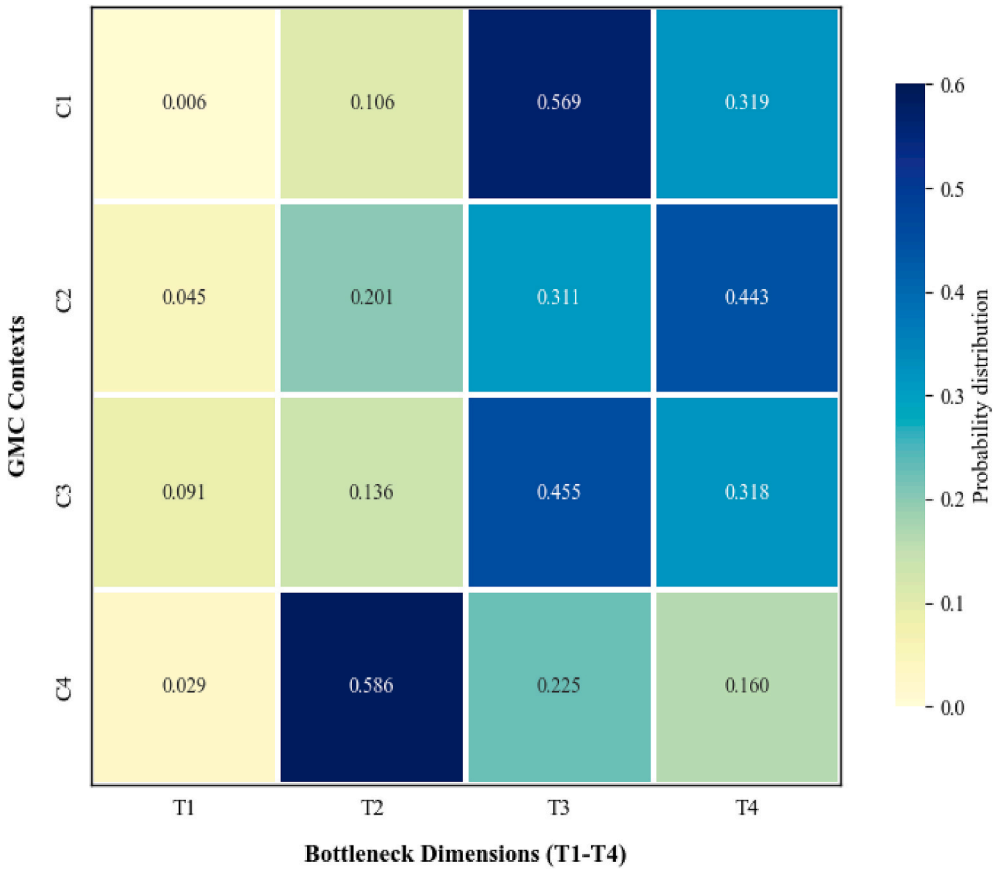


Fig. 9. Cross-context Comparison of Structural Bottleneck Patterns in Green shipping Corridors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Asia-Pacific region, (b) Trans-Atlantic and European region, (c) Trans-regional long-distance corridors, and (d) the global corpus.

In the Asia-Pacific region, the bottleneck landscape is dominated by fuel pathway and technological transition dynamics (T3), accounting for 56.9% of the identified segments. This highlights that decarbonization in this region is primarily constrained by alternative fuel identification and infrastructure readiness. Operational and sector-specific challenges (T4) represent the second-largest share (31.9%), while institutional constraints (T2) (10.6%) and system-level economic barriers (T1) (0.6%) remain secondary or negligible. As for the Trans-Atlantic and European region, this region displays a more diversified bottleneck structure, with operational and sector-specific deployment challenges (T4) emerging as the primary concern (44.3%). This suggests a shift toward the practicalities of implementation and coordination among different shipping segments. It is followed by fuel pathway issues (T3) (31.1%) and institutional governance constraints (T2) (20.1%), indicating a relatively mature policy environment compared to other regions. For Trans-regional long-distance corridors, Similar to the Asia-Pacific context, fuel pathway dynamics (T3) remain the most prominent bottleneck (45.5%), emphasizing the critical role of bunkering networks in long-haul routes. Operational challenges (T4) also contribute significantly (31.8%), while institutional (T2) and economic (T1) dimensions play auxiliary roles.

In stark contrast to specific regional findings, the global corpus is overwhelmingly preoccupied with institutional and early-stage governance constraints (T2), which comprise 58.6% of the discourse. This suggests that, at a macro level, the global community perceives knowledge accumulation, policy mobilization (e.g., Clydebank Declaration), and stakeholder coordination as the most critical hurdles. Interestingly, fuel pathway (T3) (22.5%) and operational constraints (T4) (16.0%) receive comparatively less attention in the global-scale analysis, while economic barriers (T1) remain minimal.

These results reveal a clear divergence between global discourse and regional implementation patterns. First, fuel pathway and technological transition dynamics (T3) consistently dominate across all regional corpora, particularly in Asia-Pacific region and Trans-regional long-distance corridors. This indicates that for regional stakeholders, the transition from theory to practice is first and foremost a fuel selection and bunkering infrastructure challenge.

Second, a clear trend is the high proportion of operational and sector-specific deployment challenges (T4) across all regional datasets, reaching its peak in the Trans-Atlantic and European region (44.3%). This suggests that as GSCs move toward higher maturity, the bottlenecks shift from abstract policy goals to practice operation complexities, such as vessel adaptation, route synchronization, and infrastructure updates and construction.

Third, there is a striking disparity in the perception of institutional and governance constraints (T2). At the Global level, T2 is the absolute dominant bottleneck (58.6%), reflecting a top-down focus on knowledge mobilization and international frameworks (e.g., the Clydebank Declaration). However, at the regional level, the focus on T2 significantly diminishes, suggesting that while global entities are preoccupied with how to proceed the rules and policy-driven practices, the regional actors are more concerned with handling the challenges from technical and operational perspectives.

Notably, system-level economic and scalability barriers (T1) remain consistently low in textual frequency across all contexts. This does not necessarily imply that GSCs are economically seamless; rather, it suggests that economic constraints are largely “embedded” within fuel-related discussions. As evidenced by the semantic alignment analysis, the coupling coefficient between T1 and T3 (0.57) actually exceeds the self-alignment of T1 (0.55). This strong semantic overlap indicates that a significant portion of economic bottlenecks, particularly the prohibitive costs of alternative fuels is intrinsically captured within the T3 dimension. Such a phenomenon is considered acceptable and logically sound, as fuel costs represent the most definitive economic barrier to the commercial viability of GSCs.

The results of Sections 4.3 and 4.4.2 are broadly convergent but serve different analysis purposes. Section 4.3 uses bottom-up clustering to realize the theme extraction, whereas Section 4.4.2 assesses the correspondence between textual segments and theory-informed bottleneck dimensions. The findings from these two sections therefore provide cross-method validation and complementary insights. For example, both these two analyses reveal consistent identification of T3 as the dominant dimension in the Asia-Pacific corpus and T4 in the Trans-Atlantic and European corpus. Taken together, these findings indicate that GSC development should not be interpreted as a uniform transition process, but as a regionally differentiated and stage-dependent system.

Table 4
Representative full text supporting the alternative fuel pathways policy implications.

No.	Score	Full text
ID44	0.554	Assessing clean ammonia’s ability to meet these requirements, and what this might look like over the short, medium, and long-term. The report comprises two main sections after this introduction. Section 2 establishes and describes the decarbonisation scenario that serves as a foundation for the analysis. Section 3 assesses whether a clean ammonia pathway could meet its requirements and what this might look like. Assess potential of clean ammonia to meet scenario S-curve Number of vessels and zero-emission fuel volumes.
ID37	0.546	Enhance local engagement through transparent communication, education campaigns, and incentives to build trust and support for ammonia-related projects. Delays may occur if ammonia maritime engines are unavailable when vessels are constructed. Accelerate R&D and testing timelines for dual-fuel ammonia engines and ensure collaboration between shipyards, engine developers, and vessel operators. Geopolitical events or natural disasters may disrupt the supply of essential feedstock or components for ammonia production. Diversify supplier regions and establish robust long-term contracts to ensure stable procurement of hydrogen/ammonia derivatives. Ammonia spills during production, transport, or bunkering pose significant environmental risks. Develop comprehensive disaster prevention methodologies and ensure facilities are adequately equipped without over-engineering.

5. Discussion and implications

5.1. Regional divergence in alternative fuel pathways

The divergence in regional bottleneck configurations is further substantiated by representative documents retrieved from the corpus through semantic alignment. For example, the Asia-Pacific discourse approaches the fuel pathway challenge through a temporal lens. As shown in Table 4, Document ID44 (score: 0.554) focuses on assessing *"clean ammonia's ability to meet these requirements over the short, medium, and long-term"*, reflecting a development logic in which the central question is not whether ammonia is viable, but when and under what scaling conditions it can be operationalized at corridor level. This framing indicates a relatively advanced degree of fuel commitment, while foregrounding deployment timeline uncertainty as the primary remaining constraint.

For *trans*-regional long-distance corridors, the bottleneck structure is the most complex, encompassing simultaneously technical, supply chain, and safety dimensions. Based on full text in Table 4, Document ID37 (score: 0.546) identifies three interlocking risk categories: first, the risk that *"ammonia maritime engines are unavailable when vessels are constructed"*; second, that *"geopolitical events or natural disasters may disrupt the supply of essential feedstock or components for ammonia production"*; and third, that *"ammonia spills during production, transport, or bunkering pose significant environmental risks."* These compounding constraints suggest that *trans*-regional corridor development faces a multi-layered risk environment that cannot be resolved through any single policy or technological intervention, but instead requires coordinated risk management across the entire value chain.

5.2. Regional divergence in operational strategies

Beyond fuel pathway constraints, the operational bottleneck configurations across regions exhibit equally pronounced heterogeneity, reflecting distinct implementation logics shaped by fleet structure, route characteristics, and stakeholder ecosystems.

In the Trans-Atlantic and European region, the operational challenge is fundamentally rooted in fleet heterogeneity. As shown in Table 5, Document ID7 (score: 0.609) explicitly recognizes that *"there are considerable differences between these categories in fleet structure and operating patterns"*, encompassing scheduled passenger vessels, ferries, cruise ships, cargo vessels, and specialized vessels, and concludes that *"different measures will be needed to encourage the phase-in of zero- and low-emission solutions for the different segments."* This differentiation is further compounded by route-level complexity, as illustrated by Document ID42 (score: 0.518), which highlights that certain corridors *"represent a portfolio of shipping segments, including ro-ro traffic and containerised trade, contributing to the complexity of the potential corridor."* The same document notes that stakeholder alignment remains uneven across routes, with some corridors facing *"challenging policy and stakeholder environments."* Taken together, these findings suggest that the European operational bottleneck is not a single constraint but a multi-dimensional coordination challenge arising from the coexistence of heterogeneous vessel types, diverse route profiles, and fragmented stakeholder interests.

In contrast, the Asia-Pacific region approaches operational implementation through a scale-driven logic. As shown in Table 5, Document ID35 (score: 0.556) articulates that *"if GSC route is longer, a ship service frequency is higher, and ship size is bigger, the decarbonization performance of the corridor could be better thanks to economies of scale and economies of density"*, citing the Shanghai–Los Angeles and Singapore–Rotterdam corridors as exemplary cases. This scale orientation is complemented by a supply chain integration imperative, as captured in Document ID47 (score: 0.529), which argues that corridor supply chains should encompass both *"vertical and horizontal"* dimensions, enabling major cargo owners such as Amazon and IKEA to *"contribute to achieving decarbonization of cargo and port operations throughout the supply chain in collaboration with shipping companies and terminal operators."* Together, these documents reveal that the Asia-Pacific operational logic is premised on leveraging existing high-volume trade flows and cross-actor supply chain collaboration to drive corridor viability.

For *trans*-regional long-distance corridors, the operational bottleneck shifts toward technical compliance and infrastructure

Table 5
Representative full text supporting the operational priorities among GSC development.

No.	Score	Full text
ID7	0.609	The main approach in this action plan is to consider possible measures and policy instruments for different categories of vessels: scheduled passenger vessels and ferries, cruise ships and international passenger ferries, cargo vessels, offshore support vessels, specialised vessels including aquaculture service vessels, fishing vessels and recreational craft. There are considerable differences between these categories in fleet structure and operating patterns. This means that different measures will be needed to encourage the phase-in of zero- and low-emission solutions for the different segments.
ID35	0.556	Analysis of key success factors for the implementation of the GSC First, each GSC should define specific ship type with liner service sailing on the corridor between an origin and destination ports. As the Clydebank Declaration suggested, more than two ports on the same corridor can join. Second, if GSC route is longer, a ship service frequency is higher, and ship size is bigger, the decarbonization performance of the corridor could be better thanks to economies of scale and economies of density. In this regard, the type of container ship operation is a good example as can be seen in the GSCs of Shanghai-Los Angeles/Long Beach and Singapore-Rotterdam.
ID18	0.550	The construction timeline for the fleet is designed to optimize delivery until a full fleet of ten is achieved. For the purposes of financial and emissions evaluations within this feasibility study, the operational capabilities and timelines are modeled using the full fleet of vessels. These specifications underscore the potential for technical scalability and alignment with global decarbonization efforts in maritime transport. The feasibility of implementing ammonia as a marine fuel centers around regulatory compliance, vessel design, and bunkering operations. Bulk carriers must adhere to stringent safety and environmental regulations under SOLAS and MARPOL, as well as technical standards set by classification societies to ensure alignment with IMO requirements.

precision. As shown in Table 5, Document ID18 (score: 0.550) identifies that the feasibility of ammonia as a marine fuel *"centers around regulatory compliance, vessel design, and bunkering operations"*, requiring adherence to SOLAS and MARPOL frameworks as well as classification society standards aligned with IMO requirements. At the infrastructure level, Document ID13 (score: 0.453) provides granular evidence of the engineering specificity involved, detailing that proposed bunkering solutions must optimize *"loading rates for minimal downtime"*, with a rate of 500 metric tons per hour enabling bunkering completion within an eight-hour window and resulting in a jetty utilization rate of approximately 5%, thereby providing *"significant capacity for scaling up operations as the demand for green ammonia grows."* This level of operational precision reflects a bottleneck logic shaped not by strategic ambiguity but by the engineering and regulatory requirements of long-haul ammonia deployment (Yang and Lam, 2023).

5.3. Economic viability, governance mechanisms, and institutional capacity building

It is also worth mentioning that the comparatively low standalone textual frequency of system-level economic and scalability barriers (T1) should not be interpreted as indicating that economic constraints are less important to the implementation of GSCs. Instead, the contextual evidence suggests that economic considerations are frequently embedded within discussions of fuel pathway and technological transition dynamics (T3) based on the semantic alignment analysis shown in Fig. 8.

Industry stakeholders rarely assess economic gaps independently of alternative fuel selection because each alternative fuel pathways is strongly influenced by production costs, price gaps, demand and supply stability, commercial contracts scalability, and other related factors (Long et al., 2026, DNV, 2023). Therefore, the economic and institutional dimensions of GSC development are deeply intertwined, collectively determining whether corridor initiatives can successfully transition from early-stage mobilization to large-scale commercial implementation.

The most structurally significant commercial barrier lies in the misalignment between prevailing contracting practices and the long-term capital commitments required for green fuel infrastructure. As documented in ID31 (score: 0.371), iron ore shipping on the South Africa–Europe route is currently conducted on a tramp basis with fuel purchased through spot markets or short-term agreements of less than one year, whereas green ammonia production projects require offtake agreements spanning *"over six years, preferably ten"* to secure final investment decisions.

To bridge this financing gap, the corpus identifies a range of complementary policy instruments with distinct regional applications. At the global level, Document ID99 (score: 0.361) outlines two forms of Contracts for Difference, namely a fuel-cost-based model and a total-cost-of-ownership-based model, as structured mechanisms for managing investment risk across decarbonized routes. This is reinforced by ID94 (score: 0.355), which highlights that green trade financing could lower the cost of capital sufficiently to make carbon abatement approximately self-financing, while also opening pathways for joint ventures between cargo owners and shipping lines to bridge the cost gap ahead of zero-emission fuel availability. At the regional level, Document ID73 (score: 0.371) advocates for public–private partnerships combined with financial and tax incentives, including *"discount port dues, reduction tonnage tax and green interest rates"*, as a governance model for corridors operating in competitive multi-stakeholder environments. For *trans*-regional corridors spanning emerging economies, Documents ID20 (score: 0.353), ID21 (score: 0.386), and ID24 (score: 0.398) collectively highlight that investment environments across North Africa region are further complicated by regulatory restrictions on foreign direct investment, political instability risks, and foreign exchange vulnerabilities. In response, Document ID45 (score: 0.396) proposes blended financing vehicles combining *"public or philanthropic development capital with private capital"* alongside Special Economic Zone mechanisms as viable instruments for mobilizing green infrastructure investment in high-risk corridor contexts.

Beyond financing, the institutional governance structure itself emerges as a critical determinant of corridor advancement capacity, as evident by Spiegelenberg, (2026). Document ID110 (score: 0.655) identifies a fundamental distinction between project-based governance modes. Project-based initiatives characterized by non-competitive consortia and high specificity have demonstrated a comparative advantage in navigating early preparation stages, enabling precise calculation of green premiums and funding requirements, whereas programmatic corridors report significantly greater coordination friction, including *"a decrease in the level of participation once defined"* and growing concerns around partners' *"unwillingness to share"* information. This suggests that governance mode selection is a substantive determinant of corridor progression rather than a peripheral administrative choice. Complementing this structural dimension, Document ID56 (score: 0.610) cautions against over-reliance on standardized pathways, arguing that corridor initiatives should *"lean more towards learning by doing"*, with structured best practice sharing serving as the primary mechanism through which initiatives *"gain the necessary confidence and knowledge"* to advance through development stages.

At the policy coordination level, Document ID138 (score: 0.565) underscores that effective institutional mobilization requires simultaneous engagement across multiple governance scales. The document emphasizes that *"local, port-level policies and permitting processes play a big role in the development of the corridors"* while *"national, bilateral, and regional policy measures"* remain indispensable for corridor success. This multi-scalar coordination imperative is further complicated by temporal sequencing requirements, as illustrated by Document ID48 (score: 0.485), which identifies 2028 as a realistic corridor kick-off point based on integrated assessment of technology, regulatory, and commercial development timelines. This suggests that institutional preparation must be carefully sequenced against broader system readiness conditions rather than pursued in isolation.

Taken together, these findings indicate that the economic viability and institutional governance of GSCs are not separable challenges but constitute a unified socio-technical transition problem. Resolving the green premium requires not only financial engineering but also the right governance architecture, one that aligns contractual structures with investment timelines, selects appropriate coordination models for corridor-specific stakeholder environments, and builds institutional capacity through experiential learning and multi-level policy engagement.

5.4. Policy implications and recommendations

5.4.1. Global-level policy recommendations

The findings of this study suggest that effective GSC governance cannot be designed around a one-size-fits-all framework. Instead, a differentiated policy architecture is required, one that acknowledges the structural heterogeneity of regional bottleneck configurations while providing a coherent global scaffolding within which corridor-specific action can be sequenced and coordinated. This section proposes a global policy framework organized around four interconnected imperatives: establishing differentiated governance structures, reorienting government support toward implementation, and institutionalizing adaptive learning mechanisms.

Firstly, the foundational premise of this framework is that corridor development follows a structured yet non-linear progression across four stages, namely Initiation, Exploration, Preparation, and Realisation, each characterized by distinct challenges and coordination requirements. As documented in ID26 and ID28 (scores: 0.567 and 0.574 respectively), these stages span from establishing an initiative and aligning on opportunity assessment, through removing shared barriers to realisation, to the construction and operation of zero-emission shipping infrastructure. Critically, as noted in ID25 (score: 0.606), *"phases within each progression stage can overlap"*, with pre-commercial and commercial steps potentially taken simultaneously during the Preparation stage. This non-linearity implies that policy instruments must be designed with sufficient flexibility to accommodate corridor-specific development trajectories rather than prescribing a uniform sequential pathway.

Secondly, regarding the role of government, the corpus points to a necessary evolution in policy orientation as corridors mature. Document ID5 (score: 0.594) argues that *"governments' focus should gradually move towards supporting implementation"*, encouraging governments to *"trigger a race to the top among green corridors and explore multiple policy pathways to increase the effectiveness and cost-efficiency of their support."* This reorientation implies a shift from agenda-setting and declaratory commitments toward concrete instruments, including regulatory updates, targeted tenders, and support for innovative commercial arrangements across chartering, vessel ownership, and fuel offtake structures. The governance mode selection discussed in ID110 (score: 0.655) further suggests that government-supported corridors should carefully evaluate whether a project-based or programme-based model is more appropriate given their stakeholder environment, as this choice materially affects coordination efficiency and the ability to calculate and communicate the green premium to potential investors. These findings are aligned with the studies conducted by Dolatabadi et al., (2025), Lyu et al., (2026).

Finally, the corpus consistently underscores that adaptive learning mechanisms must be institutionalized as a core component of corridor governance. Document ID158 (score: 0.589) explicitly recommends that initiatives *"lean more towards learning by doing rather than relying on a standardised path"*, recognizing that *"many aspects of green corridor development are too context-specific to be able to fully rely on standardised methodologies."* Structured best practice sharing and open discussion of challenges are identified as the primary means through which initiatives gain the market confidence.

5.4.2. Region-specific policy recommendations

While the global framework provides overarching governance principles, the structural heterogeneity identified across regional corpora necessitates differentiated policy responses tailored to the distinct bottleneck profiles of each corridor context.

In the Trans-Atlantic and European region, policy priorities should be oriented toward full value-chain transparency, multi-scalar policy coordination, and lifecycle emissions accountability. Document ID7 (score: 0.502) recommends that corridor participants be transparent not only about data but also about their roles, ensuring that *"publicly available information should also include value-chain actors such as ports, terminal operators, vessel owners and operators, charter companies, beneficial cargo owners, and others such as logistics companies."* This transparency imperative is complemented by a multi-level governance requirement, as Document ID3 (score: 0.490) emphasizes that *"national, bilateral, and regional policy measures will be key to the success of the corridors"*, with policymakers actively involved in developing corridor implementation plans. At the analytical level, Document ID8 (score: 0.461) recommends incorporating *"lifecycle-emissions estimates into equipment, materials, and fueling infrastructure planning"* alongside the establishment of publicly available baseline emissions inventories, providing a rigorous accountability framework for assessing corridor progress against decarbonization targets.

In the Asia-Pacific region, policy recommendations center on establishing clear deployment timelines, building technical workforce capacity, and adopting comprehensive corridor assessment frameworks (Douglas et al., 2025, Tae-Woo Lee et al., 2025). Document ID48 (score: 0.485) identifies 2028 as a realistic corridor kick-off point based on integrated assessment of technology, regulatory, and commercial development timelines, suggesting that near-term policy action should focus on resolving the regulatory and infrastructure preconditions necessary to meet this target. Concurrently, Document ID77 (score: 0.459) highlights crew upskilling as a critical risk factor, recommending a tripartite coordination mechanism in which fuel providers engage with maritime academies to share best practices on ammonia handling, governments fund specialized training centers for seafarers, and ship managers proactively recruit ammonia specialists. This workforce development imperative should be treated as a parallel policy priority alongside fuel infrastructure investment rather than a downstream consideration. Document ID43 (score: 0.468) further recommends adopting a three-step corridor assessment approach encompassing decarbonization scenario generation, requirements definition across vessels, fuel, and bunkering, and full-fleet feasibility analysis, ensuring that policy interventions are grounded in comprehensive route-level evidence rather than partial assessments.

For *trans*-regional long-distance corridors, the policy focus should be directed toward public finance mobilization, consortium cost synergy realization, and cargo owner commitment activation. Document ID24 (score: 0.454) establishes that "*the incremental cost burden of green corridor development reaches approximately 80 USD per tonne, with a total lifetime NPV gap of approximately 2 billion USD between green and fossil-fueled corridor configurations*". Bridging this gap requires that public funding commitments be secured as a

precondition for private investment rather than as a residual backstop. Document ID29 (score: 0.447) further identifies that corridor-level synergies can contribute up to 250 million USD in cost reductions, but notes that *"realizing these elements of cost management requires that willingness to carry from cargo and public funding is in place first."* This sequencing requirement implies that policy interventions in *trans*-regional contexts should prioritize activating cargo owner commitment through offtake frameworks and establishing blended public–private financing vehicles before advancing toward construction and operational phases.

Taken together, the global and region-specific recommendations presented in this section reflect a layered policy architecture in which universal governance principles are adapted to the distinct institutional, economic, and technical conditions of each corridor context. Effective maritime decarbonization will require not only technological readiness but also the deliberate design of governance structures, stakeholder ecosystems, and financing instruments that are calibrated to the realities of regionally differentiated implementation environments.

6. Conclusions

This study develops an advanced AI-enabled analytical framework leveraging NLP to evaluate multi-source GSC reports spanning 2021 to 2025. Our findings reveal critical bottlenecks in GSC implementation, marking the transition from high-level commitment to tangible realization from both regional and global perspectives. Furthermore, CN analysis illuminates the distinct co-occurrence structures of these bottlenecks, providing a deeper understanding of the interdependencies within regional developments.

Ultimately, this research offers evidence-based insights for industry stakeholders, policymakers, and researchers. By advancing decision-making techniques in the maritime sector, this framework supports the pursuit of sustainable development and guides strategic interventions toward a decarbonized maritime future. The core findings are summarized as follows:

(1). The thematic focus of GSC discourse varies significantly by geography. The Asia-Pacific region centers on operational coordination and route implementation; Trans-Atlantic and European regions emphasize infrastructural maturity, technological innovation, and market formation; while *trans*-regional initiatives are primarily driven by fuel production scalability, renewable energy availability, and regulatory feasibility.
(2). GSC evolution is no longer a uniform global movement but follows a "tri-polar" logic. The Asia-Pacific relies on industrial verticals for point-to-point breakthroughs; Europe establishes systemic advantages through regulatory and infrastructural maturity; and global-level frameworks provide the essential scaffolding through policy harmonization. This synergy, grounded in regional heterogeneity, is actively reshaping the global maritime landscape.
(3). Four cross-cutting themes central to GSC progress are identified: (i) systemic economic and scalability barriers; (ii) institutional and early-stage governance constraints; (iii) fuel pathways and technological transition dynamics; and (iv) sector-specific operational deployment challenges.

The findings reveal that effective green shipping corridor governance requires a differentiated policy architecture rather than a uniform framework. Regional differentiation is equally critical, as Trans-Atlantic and European corridors demand full value-chain transparency and lifecycle emissions accountability, Asia-Pacific corridors require coordinated deployment timelines and tripartite workforce upskilling mechanisms, and *trans*-regional long-distance corridors necessitate the prior activation of cargo owner commitments and blended public–private financing before infrastructure phases commence. Hence, the findings will support multi-stakeholder decision-making, including the government agencies, port authorities, shipping companies, investment departments, fuel suppliers and producers, and other related stakeholders. At the early-start stage, the decision-makers can use the identified regional bottleneck profiles for feasibility assessment, and determine which stakeholders should participate activities. For example, the port authorities can evaluate fuel supply chain readiness and prioritize the infrastructure update and investment. During GSC development, the findings can guide the sequence of policy incentives, ensuring the capital-intensive decisions and others. Cross-regional experiences can also provide transferable experiences for other GSCs facing the similar challenges.

Despite its contributions, this study has revealed several limitations. First, the current corpus is restricted to English-language documents; the exclusion of reports written in Chinese, Swedish, and Spanish corresponding to those corridors in Asian-Pacific and Europe may overlook localized strategic insights. Theoretically, including non-English-language policy documents might contribute to a more comprehensive understanding of GSC development within the relevant regions. As GSCs are an evolving concept, future research should continuously expand the database to include multilingual reports for an inclusive global analysis with the emergency of more corridors in future. Second, due to the current sample size, K-means clustering was employed to identify potential themes. As the volume of GSC reporting grows, advanced deep learning techniques could be utilized. Finally, with the rapid advancement of Large Language Models (LLMs) models, future studies should integrate AI-driven automated annotation and sentiment analysis to further decode the nuanced features of GSC developmental trajectories and compared with our findings.

CRediT authorship contribution statement

Hanwen Fan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zaili Yang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by a European Research Council project under the European Union's Horizon 2020 research and innovation programme (TRUST CoG 2019 864724).

Data availability

The authors do not have permission to share data.

References

Acciaro, M., Ghiara, H., Cusano, M.I., 2014. Energy management in seaports: a new role for port authorities. Energy Policy 71, 4–12.
Aman, J.J.C., Smith-Colin, J., Zhang, W., 2021. Listen to E-scooter riders: Mining rider satisfaction factors from app store reviews. Transp. Res. Part D: Transp. Environ. 95, 102856.
Arthur, D., Vassilvitskii, S., 2007. k-means++: the advantages of careful seeding. Proceedings of the Eighteenth Annual ACM-SIAM Symposium on Discrete Algorithms. Society for Industrial and Applied Mathematics, New Orleans, Louisiana.
Bhaduri, E., Kalatian, A., Wang, H., Choudhury, C.F., 2026. Autonomous vehicles in the public eye: a global social media analysis for smarter policies. Transp. Res. A Policy Pract. 207, 104938.
Bi, H., Gao, H., Li, A., Ye, Z., 2024. Using topic modeling to unravel the nuanced effects of built environment on bicycle-metro integrated usage. Transp. Res. A Policy Pract. 185, 104120.
Chalaris, I., Jeong, B., Jee, J., 2025. Strategic forecasting of GHG intensity: Econometrically enhanced LCA for the Singapore-Rotterdam containership green corridor. Results Eng. 28, 107437.
CITIES, C. 2022. Port of Los Angeles, Port of Shanghai, and C40 Cities Announce Partnership to Create World's First Transpacific Green Shipping Corridor Between Ports in the United States and China [Online]. Available: https://www.c40.org/news/la-shanghai-green-shipping-corridor/ [Accessed 5th,May,2026].
Corcoran, C.K., Davíðsdóttir, B., Cook, D., Jóhannsdóttir, L., 2025a. Drivers and barriers for the development and deployment of hydrogen-based fuels for the maritime sector: a case study from Iceland. Int. J. Hydrogen Energy 162, 150367.
de Freitas, L.M., Bekhor, S., Axhausen, K.W., 2025. Mode-choice modelling of a sustainable mobility transition considering different bicycle types. Transp. Res. A Policy Pract. 200, 104628.
DNV. 2023. *Energy Transition Outlook 2023: Maritime Forecast to 2050* [Online]. DNV. Available: https://www.dnv.com/maritime/maritime-forecast/ [Accessed 5th, May,2026].
Dolatabadi, S.H., Masodzadeh, P.G., Ishaq, H., Crawford, C., 2025. Green shipping corridors: an overview of Pacific Northwest region and key ports. Ocean & Coastal Management 269, 107745.
Douglas, C.M., Shanbhogue, S., Ghoniem, A., Zang, G., 2025. Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor. Appl. Energy 384, 125465.
Eldeeb, G., Mohamed, M., 2022. Transit electrification state of the art: a machine-learning based text mining approach. Transp. Res. Part D: Transp. Environ. 111, 103446.
Ellersdorfer, P., Ali Khan, M.H., Lejeune, M., Kerwick, A., Nolan, T., Martinez, J.G., Darling, A., Macgill, I., Daiyan, R., 2026. Navigating green Seas: an open-source tool for costing the development of green shipping corridors. Fuel 410, 137870.
Faivre, N., Sgobbi, A., Happaerts, S., Raynal, J., Schmidt, L., 2018. Translating the Sendai Framework into action: the EU approach to ecosystem-based disaster risk reduction. Int. J. Disaster Risk Reduct. 32, 4–10.
Garg, C.P., Kashav, V., Lam, J.S.L., 2025. Evaluation of value creating factors in green shipping corridors. Transp. Res. Part D: Transp. Environ. 145, 104790.
Ghojogh, B., Crowley, M., Karray, F. & Ghodsi, A. 2023. Uniform Manifold Approximation and Projection (UMAP). *In:* Ghojogh, B., Crowley, M., Karray, F. & Ghodsi, A. (eds.) *Elements of Dimensionality Reduction and Manifold Learning.* Cham: Springer International Publishing.
GLOBAL MARITIME, F. 2021. The Next Wave Green Corridors: A Special Report for the Getting to Zero Coalition. Global Maritime Forum.
Global Maritime Forum 2025. Annual Progress Report on Green Shipping Corridors 2025. Global Maritime Forum.
Gore, K., Rigot-Müller, P., Coughlan, J., 2022. Cost assessment of alternative fuels for maritime transportation in Ireland. Transp. Res. Part D: Transp. Environ. 110, 103416.
Ismail, A.M., Ballini, F., Ölçer, A.I., Alamoush, A.S., 2024. Integrating ports into green shipping corridors: drivers, challenges, and pathways to implementation. Mar. Pollut. Bull. 209, 117201.
Kian, H., Galimova, T., Breyer, C., 2026. Review of maritime defossilisation regarding regulation, energy efficiency, alternative fuels, and technologies. Renew. Sustain. Energy Rev. 234, 116895.
Lee, P.-T.-W., Kim, G.S., Tran, D.P., Feng, X., Nkhoma, M., Visamitanan, K., Nari, H.P., Muangpan, T., Shin, S.-H., 2026. A conceptual model of Mekong River green corridors for inland water transport and logistics. Int J Log Res Appl 1–20.
Li, Y., Wang, S., Tang, J.H.C.G., Peng, Z., Zhuge, C., 2024. Public attention and attitudes towards bike-sharing in China: a text mining approach. Transp. Res. Part D: Transp. Environ. 134, 104348.
Liu, M., Yao, Q., Pang, X., Yan, W., 2026. Evaluating the carbon reduction of shore power for green shipping corridor development. Ocean Eng. 354, 124914.
Lloyd, S.P., 1982. Least squares quantization in PCM. IEEE Trans. Inf. Theory 28, 129–136.
Long, S., Zhao, H., Wang, Y., Wu, L., 2026. Strategy selection of competitive ports and the information value of digital twin in the construction of green shipping corridors. Transportation Research Part e: Logistics and Transportation Review 215, 104912.
Lyu, X., Jin, J.G., Wang, Z., 2026. Towards net-zero shipping: a multi-level optimization model for green maritime corridors integrating bunker network, ship routes, and fleet deployment. Transportation Research Part e: Logistics and Transportation Review 206, 104595.
Lyu, X., Li, M., 2025. Cost-effective and carbon policy-driven network design optimization for Green Maritime Corridors: case studies in the Baltic, Mediterranean, and Pacific regions. Energy 341.
Malaghan, V., Pilla, F., Tafidis, P., Rogers, B., 2025. Behavioral insights and hotspot identification: integrating natural language processing, machine learning and geospatial analyses of cyclist crashes. Transport. Res. F: Traffic Psychol. Behav. 113, 452–480.
Mohammadpour, J., Salehi, F., 2025. A review of alternative liquid fuels in marine engines. Appl. Energy Combust. Sci. 24, 100394.
MæRSK. 2022. *Green Corridors: Feasibility Phase Blueprint* [Online]. Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. Available: https://cms.zerocarbonshipping.com/media/uploads/documents/220929_Green-Corridors_Feasibility-Blueprint.pdf [Accessed 5th,May,2026].
Rath, S., Chow, J.Y.J., 2022. Worldwide city transport typology prediction with sentence-BERT based supervised learning via Wikipedia. Transp. Res. Part C Emerging Technol. 139, 103661.

Ruslan, S.M.M., Osman, M.T., Mansor, W.N.W., Mokhtar, K., Saidi, N., Roslan, U.A.M., Hassim, M.F.N., McLellan, B.C., 2025. Winning the carbon race: game-based strategies for emission reduction in maritime industry. Res. Transp. Bus. Manag. 61, 101409.
Shao, S., Xu, M., Tan, Z., Zhen, L., 2024. Ship deployment problem with green technology adoption for an inland river carrier under non-identical streamflow and speed limits. Transp. Policy 157, 46–56.
Solakivi, T., Paimander, A., Ojala, L., 2022. Cost competitiveness of alternative maritime fuels in the new regulatory framework. Transp. Res. Part D: Transp. Environ. 113, 103500.
Song, Z.-Y., Chhetri, P., Ye, G., Tae-Woo Lee, P., 2025. Green maritime logistics coalition by green shipping corridors: a new paradigm for the decarbonisation of the maritime industry. Int J Log Res Appl 28, 363–379.
Spiegelenberg, F., 2026. Delivering a just and equitable transition: alternatives for effective and credible management of shipping's climate funds. Global Maritime Forum, Copenhagen.
Tae-Woo Lee, P., Song, Z.-Y., Chhetri, P., Shin, S.-H., 2025b. China's twin strategic development of iron-ore imports along the maritime silk road: economic security and decarbonization of maritime industry. Ocean & Coastal Management 260, 107483.
Tomos, B.A.D., Stamford, L., Welfle, A., Larkin, A., 2024. Decarbonising international shipping – a life cycle perspective on alternative fuel options. Energ. Conver. Manage. 299, 117848.
Wagner, N., 2025. Towards sustainable maritime transport: Focus on the early phase of technology development related to alternative fuels. Energy Sustain. Dev. 85, 101686.
Wang, H., Daoutidis, P., Zhang, Q., 2023. Ammonia-based green corridors for sustainable maritime transportation. Digital Chem. Eng. 6, 100082.
Wang, Q., 2025. Managing emerging port security challenges in developing green and digital shipping corridors: a port governance cooperation perspective under the Belt and Road Initiative. Ocean & Coastal Management 270, 107924.
Wang, Y., Iris, Ç., 2025. Transition to near-zero emission shipping fleet powered by alternative fuels under uncertainty. Transp. Res. Part D: Transp. Environ. 142.
Wang, Y., Liu, J., Liu, Y., Wang, J., Di, Z., 2025. Optimizing multi-type demand-driven Ro-Ro fleet scheduling in high-density maritime corridors. Reg. Stud. Mar. Sci. 89, 104369.
Wei, J., Kan, Z., Kwan, M.-P., 2026. Revealing sequential activity-travel patterns and spatial structures among older and younger adults from smart card data. Transp. Res. A Policy Pract. 203, 104749.
Yan, Z., 2024. Establishment of urban green corridor network based on neural network and landscape ecological security. Journal of Computational Science 79, 102315.
Yang, M., Lam, J.S.L., 2023. Operational and economic evaluation of ammonia bunkering – bunkering supply chain perspective. Transp. Res. Part D: Transp. Environ. 117, 103666.
Zhang, C., Lin, H., Hao, H., Chen, Y., 2026. How do electric vehicles impact community resilience? a bi-Layer network perspective. Transp. Res. Part D: Transp. Environ. 150, 105075.
Zhang, S., Feng, C., 2024. Evolutionary game model for decarbonization of shipping under green shipping corridor. International Journal of Low-Carbon Technologies 19, 2502–2511.
Zhao, M., Chen, S., Sun, Y., 2026. Uncovering thematic correlations across transportation research journal series: pitting human expertise against machine intelligence. Transp. Res. A Policy Pract. 206, 104901.
Zhou, Y., Zhai, J., 2026. Preserving the past, cultivating the future: integrating canal heritage with blue-green infrastructure in composite corridors for Canal Cultural Park planning. Environmental Development 57, 101384.