Asian ammonia hubs: Economic feasibility of transshipment

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Abstract:

As the global transition toward low-carbon energy systems accelerates, the importance of cross-regional trade in low-carbon ammonia has become increasingly evident. This study develops a maritime logistics model for the hub-and-spoke mode. Ammonia is transported in large vessels to an Asian ammonia hub and subsequently redistributed using smaller vessels. Singapore is selected as a case study for the ammonia hub. In the conservative baseline scenario, each importing country relies on a single port. Results show that the hub-and-spoke mode yields lower transport costs on 17 out of 26 routes, over 65%. On the Saudi Arabia-Thailand route, it achieves a reduction in cost by approximately 52.2% compared with direct shipping. However, for some countries with higher import demand, direct shipping becomes more economically feasible. The hub-and-spoke mode reduces costs through trunk-route economies of scale and better demand matching, but its advantage diminishes at high volumes where direct shipping avoids additional distribution costs. The realistic scenario is also considered: ammonia import terminals in those large-scale import countries are geographically dispersed. The economic advantages of the hub-and-spoke model begin to emerge and sometimes exceed those of direct routes.

Keywords:

Ammonia trade; Maritime Logistics; Hub-and-Spoke Model; Economic Analysis; Energy Transition.

1. Introduction

As an efficient carrier for hydrogen storage and transportation, low-carbon ammonia is widely regarded as a key pathway for enabling large-scale deployment of hydrogen energy, and is expected to play a strategic role in future global energy systems [1, 2]. According to the International Energy Agency (IEA) [3], approximately 120 hydrogen-based fuel terminal and port infrastructure projects, which primarily focus on ammonia handling, are expected worldwide by the end of the decade.

Low-carbon ammonia is becoming one of the most promising hydrogen derivatives in the energy sector during the transition phase towards decarbonization. Compared to hydrogen, ammonia is better suited for large-scale and for long-distance transport, effectively overcoming the limitations of hydrogen. Therefore, for many Asian countries, importing low-carbon ammonia is vital for achieving energy security and sustainability. Long-distance maritime routes primarily transport ammonia imports in Asia. However, taking into account the increased demand, developing innovative logistics is essential to minimize the costs of so-called “low-carbon” ammonia. Some Asian countries have already developed plans to establish ammonia hubs; these hubs are primarily intended to enable energy-oriented large-scale ammonia imports and cracking. The Asian ammonia market is highly heterogeneous:

- *by resources* - substantial downstream potential for low carbon ammonia applications, but are constrained by limited to domestic renewable energy, which restricts their ability to achieve large-scale production [4];
- *by demand scale* - import can differ by several orders of magnitude across countries, resulting in the coexistence of small scale, decentralized deliveries and large-scale, or concentrated demand [5]. High uncertainty associated with shipping, e.g., vessel utilization rates, choice of maritime modes, etc., will affect transportation cost estimation, and
- *by supply sources and trade logistics* - ammonia supply to Asian countries is highly diversified, by traditional producers within the region and external suppliers from the Middle East and Oceania [6]. Differences across supply sources in terms of transport distance, route characteristics, and supply stability further increase the complexity of the logistical planning within the region.

Maritime shipping is currently the dominant method for cross-regional ammonia transport in Asia and worldwide, and is expected to remain central to future low-carbon ammonia trade. Its costs will influence supply chain economics and constitute a key constraint on the feasibility of cross-regional flows. Ammonia trade between Asia and major exporting regions is typically organized as direct origin-to-destination flows between dedicated terminals with limited transshipment. However, as heterogeneity increases, whether conventional direct shipping consistently offers cost advantages across countries and shipment scales remains to be systematically assessed.

Despite the growing number of such proposals, the economic feasibility of ammonia hubs as regional transshipment nodes in Asia remains insufficiently assessed. Therefore, it is important to evaluate whether a hub-and-spoke shipping mode offers cost advantages over direct shipping, and to identify the shipment scales at which these advantages arise.

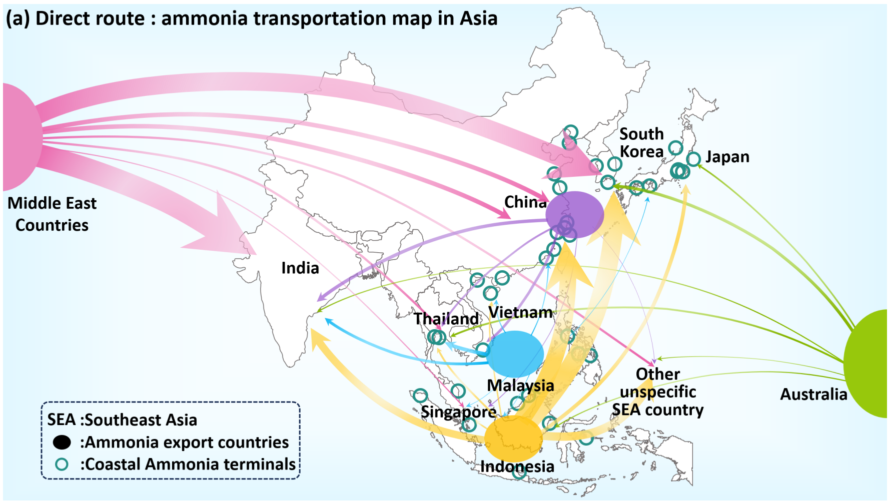
To tackle the above issues, this study develops a maritime ammonia shipping cost model that departs from the commonly used full-load, single-vessel assumption. The model endogenously determines fleet size at the route level based on transport demand. When demand exceeds the annual capacity of a single vessel, additional vessels are deployed discretely; When capacity exceeds demand, reduced utilization is explicitly reflected in higher unit transport costs, capturing diminishing returns to scale.

2. Overall ammonia transportation routes in Asia

This study is based on ammonia trade data from 2023, which is the most recent year for which data are available. The ammonia trade involving Asia can be categorized into two types:

- *intra-regional trade* - Indonesia (accounting for approximately 75% of total intra-Asian ammonia exports) and Malaysia (approximately 17%) currently represent the dominant exporting countries. Ammonia production in both countries relies heavily on natural gas as the primary feedstock. By comparison, China also maintains a certain level of ammonia exports, but its share in intra-regional trade remains relatively limited.
- *cross-regional trade* - the Middle East region countries (Saudi Arabia, Qatar, Oman, Bahrain, and the United Arab Emirates) constitute the most significant supply source, collectively accounting for more than 92% of Asia's extra-regional ammonia imports. In addition to the Middle East, Australia in Oceania also represents an important source of ammonia imports for Asian markets. At present, India, China, South Korea, and Thailand are among the major importers of ammonia originating from these regions.

Figure 1 illustrates the maritime shipping structure for ammonia from Asia in 2023 [6]. Line thickness corresponds to trade flow volumes. The figure also marks the spatial distribution of existing ammonia coastal storage terminals for July 2025 [7].



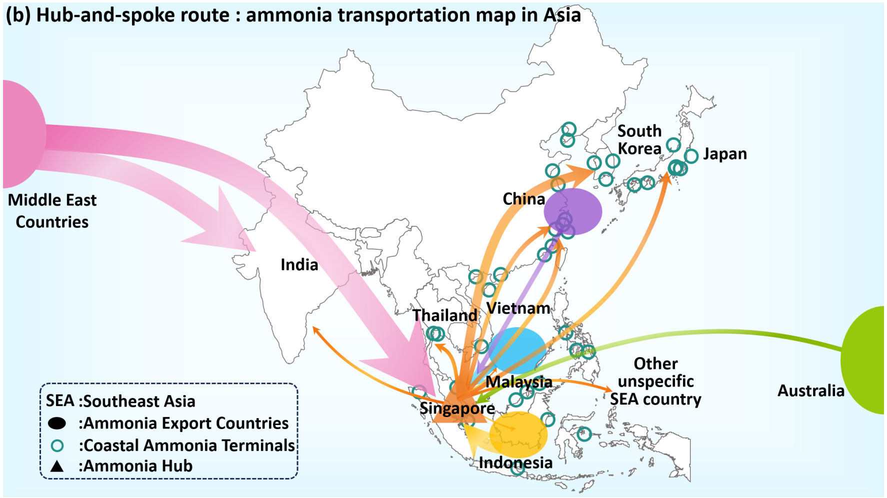


Figure. 1. *Schematic of Asian ammonia maritime trade routes in 2023: a) direct shipping mode, and b) the hub-and-spoke shipping mode (Singapore is selected as a case study for the ammonia hub).*

3. Numerical model and associated parameters

3.1. Model description

In the direct shipping mode, liquid ammonia is loaded into storage tanks at the export terminal for short-term storage before loading. Later, it is transported directly to the import terminal in the importing country. Upon arrival at the import terminal, the liquid ammonia is unloaded and temporarily stored in tanks before further utilization. In the hub-and-spoke transshipment mode, liquid ammonia is first transported in bulk by larger ammonia carriers to an intermediate country that hosts an ammonia hub, where it is temporarily stored in terminal tanks. Subsequently, the ammonia stored at the hub is redistributed by smaller vessels and delivered to the destination country terminals. The overall modeling scope and computational logic of the study are illustrated in Figure 2.

For the simplification of analysis, the following is not included in this study: (a) costs associated with upstream ammonia production in the supply chain (hydrogen production, hydrogen transport to ammonia synthesis facilities, ammonia synthesis, and subsequent liquefaction processes); (b) costs related to downstream utilization, such as the direct use of ammonia as a fuel or ammonia cracking for hydrogen recovery, and (c) inland transport costs, whether by road or pipeline, from production sites to export terminals are excluded from the analysis (indicated by the shaded area in Figure 2).

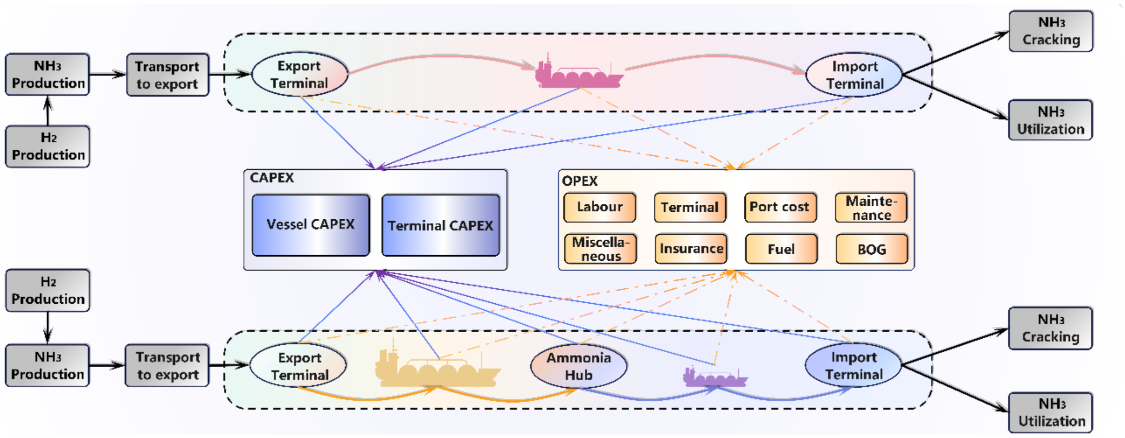


Figure. 2. *The process of transportation cost calculation model of the direct and hub-and-spoke modes.*

3.2. Direct route calculation model

Cost models for ammonia maritime transport typically rely on full-load assumptions, which fail to account for the heterogeneity observed in real-world Asian trade (e.g., [8]). To address this limitation, the cost model is adjusted by introducing a volume-driven mechanism, under which annual transport volume becomes the key constraint in determining route-level cost performance. For simplicity, the overall modeling procedure is described in the text rather than in nomenclature.

3.2.1. *Voyage time and annual trip capacity*

For each vessel type, the one-way sailing time (Days_One Way) is calculated based on design speed and sailing distance:

$$Days\_One\ Way\ (days) = \frac{Distance\ (nautical\ miles)}{Speed\ (knots) \times 24} \tag{1}$$

Considering round-trip sailing and loading/unloading operations at both export and import terminals, the total time required for a vessel to complete one full round trip (Total Trip Time) is given by:

$$Total\ Trip\ Time\ (days) = Days\_One\ Way \times 2 + Port\ Days\ \times 2, \tag{2}$$

where the term "Port Days" denotes the time required for loading or unloading at a single port.

Given the operating conditions, the Rated Annual Trips that a vessel of a given type can complete on a specific route is calculated as:

$$Rated\ Annual\ Trips = \frac{Days\ Per\ Year\ In\ Operation}{Total\ Trip\ Time} \tag{3}$$

3.2.2. *Shipment volume-driven adjustment mechanism*

In practice, the annual shipment demand on each route is typically treated as an exogenous, rigid constraint. To relax the implicit full-load assumption, this study introduces an Annual Transport Quantity Adjustment Factor, denoted by ε. Under design conditions, the annual number of trips completed by a single vessel is determined by its rated operating capability. The adjustment factor ε then scales the vessel trip frequency, thereby determining the total annual number of trips required (Annual Trips).

$$Annual\ Trips = Rated\ Annual\ Trips \times \varepsilon, \tag{4}$$

On this basis, the annual delivered quantity is determined by the annual trips and the cargo capacity of a single vessel, which is calculated as follows:

$$Annual\ Delivered\ Quantity\ (kg) = Annual\ Trips \times Ship\ Capacity\ (kg) \tag{5}$$

With the introduction of ε, when the full-load capacity of a single vessel exceeds route-level demand, ε takes a value smaller than 1, indicating reduced vessel utilization and a corresponding decrease in delivered volume. Conversely, when the annual transport demand on a route exceeds the annual carrying capacity of a single vessel, ε becomes greater than 1, thereby triggering fleet expansion through the deployment of additional vessels to satisfy the excess demand. Through this mechanism, ε directly determines the transport capacity of the route by adjusting the annual number of trips.

In the model, the value of ε is iteratively determined according to the following criterion below, such that the resulting annual delivered quantity matches the actual transport demand on the route:

$$Annual\ Delivered\ Quantity = Actual\ Transport\ Quantity\ On\ Route \tag{6}$$

Notably, the adjustment mechanism of ε also captures cost variations associated with vessel fully or partially loaded operations. When ε takes a non-integer value, the required number of vessels is determined by rounding ε up to the nearest integer ($\lceil \varepsilon \rceil$). For example, when ε = 1.2, two vessels are assigned to the route, and the corresponding capital costs as well as other vessel number-dependent costs are counted as twice those of a single vessel. By introducing ε, the proposed framework fundamentally extends the applicability of conventional maritime transport cost models beyond the implicit full-load assumption.

Annual Sailing Days plays a critical role in calculating fuel consumption and boil-off gas (BOG) losses. They are determined as:

$$Annual\ Sailing\ Days = Annual\ Trips \times Days\ One\ Way \times 2 \tag{7}$$

3.2.3. Annual Cost Structure

The total annual cost is defined as the sum of annual CAPEX and OPEX:

$$Total\ Annual\ Cost\ \left(\frac{MUSD}{year}\right) = Annual\ CAPEX + Annual\ OPEX \tag{8}$$

3.3. Capital expenditure

Annual Capital expenditure (CAPEX) is obtained by annualizing the Vessel Capital Cost and the Allocated Terminal Capital Cost:

$$Annual\ CAPEX\ \left(\frac{MUSD}{year}\right) = CRF \times (Vessel\ Captial\ Cost + Allocated\ Terminal\ Capital\ Cost) \tag{9}$$

3.3.1. Capital recovery factor

The Capital Recovery Factor (CRF) is calculated as follows:

$$CRF = \frac{(i \times (1+i)^N)}{((1+i)^N - 1)} \tag{10}$$

Where i denotes the interest rate and N the economic lifetime (years).

3.3.2. Capital recovery factor

The total vessel capital cost is determined by the capital cost of a single vessel and the number of vessels deployed on the route, given by $[\varepsilon]$. It is calculated as follows:

$$Vessel\ Captial\ Cost\ (MUSD) = Capital\ Cost\ For\ Single\ Vessel \times [\varepsilon] \quad (11)$$

3.3.3. Terminal capital cost

Terminal capital cost consists of ammonia storage systems, vessel connection pipelines, and the jetty, with its associated infrastructure. The cost components are based on the calculation framework of the HDSAM database developed by Argonne National Laboratory [9].

Accordingly, the total terminal capital cost is expressed as:

$$Terminal\ Captial\ Cost\ (MUSD) = Storage\ Capital\ Cost + Pipeline\ Capital\ Cost + Jetty\ with\ Associated\ Infrastructure\ Capital\ Cost \quad (12)$$

The capital costs of individual components can be estimated by linearly scaling the costs of reference-sized equipment:

$$Storage\ Captial\ Cost\ (MUSD) = Storage\ Reference\ Cost \times \left(\frac{Nominal\ Storage\ Capacity}{Reference\ Storage\ Capacity}\right) \quad (13)$$

$$Pipeline\ Capital\ Cost = Pipeline\ Reference\ Cost \times \left(\frac{Pipeline\ Nominal\ Capacity}{Pipeline\ Reference\ Capacity}\right) \quad (14)$$

The nominal capacity of the pipelines is determined by the cargo capacity of the ammonia carrier to which they are connected.

The capital cost of the jetty with its associated pipelines and other infrastructure is calculated as:

$$Jetty\ Capital\ Cost = Jetty\ Reference\ Cost \times \left(\frac{Jetty\ Nominal\ Capacity}{Jetty\ Reference\ Capacity}\right) \quad (15)$$

Similarly, nominal capacities for a jetty with its associated pipelines and other infrastructure are also determined by the cargo capacity of the ammonia carrier served.

3.4. Route-level allocated terminal capital cost

Based on the global ammonia infrastructure statistics published by the International Maritime Organization (IMO) [5], data on the total existing ammonia storage capacity for each country are obtained. The total terminal capital investment is first estimated at the country level based on the aggregate storage capacity of all terminals. As this capacity supports all ammonia trade routes within the country, the terminal capital cost is allocated to individual routes in proportion to their share of the country's total annual handling volume, derived from global ammonia trade statistics [6].

The allocated terminal capital cost for each route is therefore expressed as:

$$Allocated\ Terminal\ Capital\ Cost\ (MUSD) = Terminal\ Captial\ Cost \times \left(\frac{Route\ Annual\ Volume}{National\ Annual\ Import/Export\ Volume}\right) \quad (16)$$

3.5. Annual Operating expenditure (OPEX)

The annual operating expenditure (OPEX) is decomposed into the following components:

$$Annual\ OPEX\ \left(\frac{MUSD}{year}\right) = Labour\ Cost + Terminal\ Operating\ Cost + Port\ Cost + Maintenance\ Cost + Miscellaneous\ Cost + Insurance\ Cost + Fuel\ Cost + BOG\ Cost + Carbon\ Cost \quad (17)$$

Labor cost is estimated using an aggregate approach, with values differentiated by vessel type**.**

Terminal operating cost is calculated as a fixed percentage of the allocated terminal capital cost:

$$Terminal\ Operating\ Cost\ (MUSD) = Allocated\ Terminal\ Capital\ Cost \times Terminal\ Operating\ Rate\ (\%). \quad (18)$$

Port cost represents the various charges incurred by vessels at export and import ports and is calculated as follows:

$$Port\ Cost\ (MUSD) = Annual\ Trips \times Port\ Days \times \left(Port\ charges\ Export\ \left(\frac{MUSD}{day}\right) + Port\ charges\ Import\ \left(\frac{MUSD}{day}\right)\right) \quad (19)$$

Furthermore, port charges can be decomposed as

$$Port\ Charges\frac{Export}{Import}\left(\frac{MUSD}{day}\right) = Port\ Dues + Pilotage\ And\ Pilot\ Boat\ Charges + Towage\ And\ Tug\ Boat\ Charges + Wharfage\ And\ Liquid\ Ammonia\ Handling\ Charges \quad (20)$$

Given that Port Charges for Export/Import may vary across countries, country-specific values are used in the model.

Maintenance cost is also calculated as a fixed percentage of the vessel capital cost:

$$Maintenance\ Cost\ (MUSD) = Vessel\ Capital\ Cost \times Maintenance\ Rate\ (\%). \quad (21)$$

For miscellaneous cost:

$$Miscellaneous\ Cost\ (MUSD) = (Labour\ Cost + Port\ Cost + Maintenance\ Cost + Terminal\ Operating\ Cost) \times Miscellaneous\ Rate\ (\%) \quad (22)$$

Calculation of the insurance cost takes a similar pathway:

$$Annual\ Insurance\ Cost\ (MUSD) = (Labour\ Cost + Port\ Cost + Maintenance\ Cost + Terminal\ Operating\ Cost) \times Insurance\ Rate\ (\%) \quad (23)$$

Fuel cost is determined based on the vessel's fuel consumption and the fuel price, which is calculated as follows:

$$Fuel\ Cost\ (MUSD) = Fuel\ Consumption\ (tonnes) \times Fuel\ Price\ \left(\frac{USD}{tonne}\right) \times 10^{-6} \quad (24)$$

$$Fuel\ Consumption\ (tonnes) = Annual\ Sailing\ Days \times Fuel\ Used\ Per\ Day\ \left(\frac{tonnes}{day}\right) \quad (25)$$

$$Fuel\ Used\ Per\ Day\left(\frac{tonnes}{day}\right) = \frac{Ship\ Energy\ Required\ (\frac{MWh}{day})\times 3.6}{Fuel\ Energy\ Content\ (\frac{MJ}{kg})} \quad (26)$$

$$Ship\ Energy\ Required\ \left(\frac{MWh}{day}\right) = \frac{Ship\ Engine\ Capacity\ (MW)\times 24}{Ship\ Engine\ Efficiency\ (\%)} \quad (27)$$

BOG cost is determined based on the BOG rate during sailing, the ammonia price, and other related parameters, which is calculated as follows:

$$BOG\ Cost\ (MUSD) = Annual\ Sailing\ Days\ (day) \times BOG\ Rate\ \left(\frac{\%}{day}\right) \times Ship\ Capacity\ (kg) \times \frac{Lower\ Heating\ Value\ (\frac{MJ}{kg})}{1000} \times Ammonia\ Price\ \left(\frac{USD}{GJ}\right) \times 10^{-6} \quad (28)$$

Based on the above formulations, the unit transport cost of ammonia can be calculated as:

$$Cost\ Per\ kg\ Ammonia\ \left(\frac{USD}{kg}\right) = \frac{Total\ Annual\ Cost\ (MUSD/year)}{Annual\ Delivered\ Quantity\ (kg/year)} \times 10^{6} \quad (29)$$

Under the hub-and-spoke transport configuration involving ammonia hubs, the total transport cost is calculated by separately evaluating two components: the trunk-haul segment operated by larger vessels and the feeder distribution segment served by smaller vessels. These components are modeled separately and subsequently aggregated to obtain the total cost. In addition, the shipment volumes of the two segments are independently regulated by two adjustment factors, ε_A and ε_B, respectively.

The corresponding terminal capital expenditure is expressed as:

$$Terminal\ CAPEX\ (Hub\ and\ Spoke) = Export\ Terminal\ CAPEX + Hub\ Terminal\ CAPEX\ + Import\ Terminal\ CAPEX \quad (30)$$

Other cost components are treated consistently with those in the direct shipping mode. Overall, the proposed model establishes a unified framework for estimating and comparing ammonia maritime transport costs across diverse shipping modes and configurations, while explicitly accounting for volume heterogeneity and multi-stage transport structures.

3.6. Model assumptions and associated key parameters

Due to limitations in real-world trade data availability, certain aspects of ammonia trade within Asia are not directly observable or cannot be disaggregated at the required level of detail. Accordingly, a set of reasonable assumptions is introduced in the modeling process.

A. Assumptions for some importers

1. Allocation of imports reported as "Other unspecified Asian countries". In the World Bank trade statistics, ammonia import volumes for some unspecified countries are aggregated and reported under the category "Other unspecified Asian countries", and this category accounts for a relatively large share. Given that some major Asian ammonia importers (such as South Korea, China, and India) are explicitly reported in the dataset, this study assumes that the unspecified category primarily corresponds to several smaller Southeast Asian countries whose imports are not individually disclosed in existing records. To avoid potential bias arising from allocating this aggregated import volume to a single country, a mean approach is adopted. Specifically, based on the total number of Southeast Asian countries and the number of countries already reported in the trade

data, the remaining 7 unspecified Southeast Asian importers are assumed to evenly share the total import volume reported under “Other unspecified Asian countries.” Such treatment is intended to approximate the small-scale and decentralized import characteristics of these countries. It should be noted that this assumption is mainly introduced to capture the aggregate transport organization features of small importers and does not materially affect the results for other importing countries in the model.

2. Assumptions regarding ammonia receiving terminals. Publicly available information on ammonia import terminals varies significantly across countries, ranging from well-documented cases to regions with incomplete or missing information. To control for confounding factors and ensure comparability across different transport pathways, this study assumes ammonia demand in each importing country is received and handled by a single terminal in the base case analysis

B. Assumptions regarding the exporters

1. For the Middle East, this study assumes that ammonia exports from each exporting country are shipped through a single representative port. As ammonia export terminals in the Middle East are predominantly located along the Persian Gulf coastline and are geographically highly concentrated, this assumption does not introduce bias in the results arising from transport distance estimation.

2. Similarly, ammonia exports from Australia are assumed to be shipped through a single export port called Dampier in the Pilbara region. This port is selected as the representative export node for distance calculations. The Pilbara region has long been a key area through which Australia participates in global ammonia trade [10,11]. In this area, Yara operates an ammonia facility with an annual production capacity of approximately 0.85 Mt, around 70% of which is exported, primarily through the Port of Dampier [12].

C. Selection of ammonia carriers, with other technical parameters

With respect to ammonia carrier size selection, existing studies often adopt capacity assumptions analogous to those for LNG carriers, with limited consideration of the practical size constraints of the current ammonia-capable fleet. However, such assumptions of large vessel sizes under full-load operation may lead to a systematic underestimation of maritime ammonia transport costs. In practice, most vessels currently used for ammonia transport are converted from liquefied petroleum gas (LPG) carriers and have significantly smaller capacities than typical LNG carriers. Figure 3 presents the distribution of vessel sizes and construction years for the existing LPG fleet applicable to ammonia transport (hereafter referred to as ammonia carriers). The black dots represent individual ammonia-capable vessels, while the dashed line indicates the fitted trend of cargo tank capacity over time. The largest currently feasible ammonia carriers are around 50000 deadweight tonnage (DWT), but they account for only a small share of the fleet. In contrast, vessels in the 15000-30000 DWT range are most densely distributed and constitute the backbone of the existing ammonia carrier fleet. The fitted trend further suggests a noticeable increase in vessel size over time, indicating that, under continued technological progress and evolving market conditions, there remains potential for future scaling of ammonia carrier capacities.

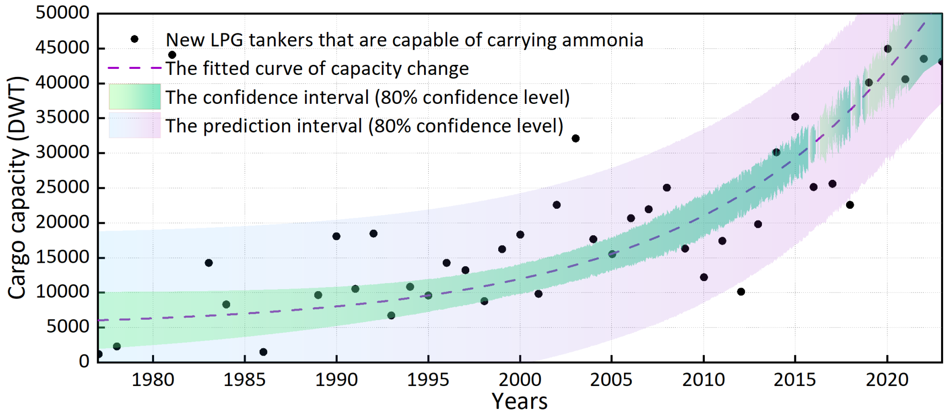


Figure. 3. *Build years, number, and capacity of LPG carriers suitable for ammonia transport, and their temporal trends (adapted from [13]).*

Based on these practical engineering constraints, the model adopts three representative ammonia carrier sizes to evaluate transport cost performance across different shipment volume conditions.

Specifically, the selected vessel types include a Large Gas Carrier (LGC) with a capacity of 50000 t, a Medium Gas Carrier (MGC) with a capacity of 28000 t, and a Small Gas Carrier (SGC) with a capacity of 8000 t. Port days are calculated as the vessel's capacity divided by the loading/unloading rate. Depending on vessel characteristics and terminal scale, ammonia loading and unloading rates can exceed 1000 tonnes per hour [14, 15]. Therefore, the loading/unloading rate of 1200 t/h is assumed in this study. The annual labor cost per vessel is based on literature values for LGC, with similar magnitudes applied to other vessel types.

The technical specifications of ammonia carriers across size categories and serve as key inputs to the subsequent modeling can be found in [8, 16-19]. Key technical parameters are summarized in Table 1.

Table. 1. *Other key technical parameters assumed in this study*

Parameters	Unit	Value	Ref.
Days per year in operation of the vessel	Days	350	[8]
Economic life	Years	30	[8]
Storage reference cost	MUSD	50	[9]
Storage reference capacity	m^3	58000	[9]
Storage nominal capacity	m^3	Differs depending on countries	-
Pipelines for vessel reference cost	MUSD	3.3	[9]
Pipelines for vessel reference capacity	m^3	51000	[9]
Pipelines for vessel nominal capacity	m^3	Differs depending on vessel type	-
Jetty with its infrastructure reference cost	MUSD	3.366	[9]
Jetty with its infrastructure reference capacity	m^3	51000	[9]
Jetty with its infrastructure nominal capacity	m^3	Differs depending on vessels	-
Fuel energy content (VLSFO)	MJ/kg	40	-
Fuel cost (VLSFO)	USD/ton	638 (2023)	-
BOG rate	%	0.004	[8]
Ammonia cost	USD/GJ (LHV)	45.8	-
Lower heating value (LHV) of NH_3	MJ/kg	18.6	-
Maintenance cost	%	4	[8]
Miscellaneous cost	%	10	[8]
Insurance cost	%	10	[8]
Terminal OPEX	%	4	[8]
Carbon emission factor (CO_2 equal)	gCO_2e/g VLSFO	3.16	-

4. Case study: The ammonia hub in Singapore

At present, several Asian countries have proposed developing ammonia hubs at their ports to support the anticipated expansion of ammonia trade and the deployment of future energy-related applications.

As an established maritime and trading hub in Asia, Singapore is well-positioned to evolve into a regional hydrogen and ammonia energy hub, supported by its strategic location, strong economic foundation, and well-developed institutional framework [20, 21]. Moreover, Singapore has already established mature business models for transshipment and redistribution in the LNG trade, providing practical experience highly relevant to hub-based ammonia shipping [22].

Building on these considerations, this study selects Singapore as a representative regional hub for a case study to quantitatively examine the economic characteristics of hub-and-spoke maritime shipping in the Asian ammonia trade. Under this scenario, ammonia is first transported in bulk to the Singapore hub by relatively large-capacity vessels and subsequently distributed to importing Asian countries using smaller vessels.

Not all transport routes are considered in this study. Given the close geographical proximity of Singapore to Malaysia and Indonesia, routing ammonia exports from these countries through the Singapore hub for onward delivery to other East and Southeast Asian destinations would introduce redundant transport pathways and be inconsistent with rational trade organization. Similarly, ammonia exports from the Middle East to India do not require transshipment via Singapore due to geographical considerations. These transport routes are therefore excluded from the case analysis.

In the hub-and-spoke mode, the consolidated transport volume handled by the Singapore hub equals the aggregate ammonia export volumes from all exporting countries supplying the Asian market.

Taking the Middle East as an example, the total volume of ammonia exports from the Middle East handled by the Singapore (SG) hub can be expressed as the sum of exports from individual Middle Eastern countries (Saudi Arabia (SA), Bahrain (BH), Oman (OM), Qatar (QA), United Arab Emirates (UAE)) to Asian markets:

$$V_{ME\to SG} = V_{SA\to SG} + V_{BH\to SG} + V_{OM\to SG} + V_{QA\to SG} + V_{UAE\to SG}, \quad (31)$$

where $V_{ME\to SG}$ denotes the total ammonia volume from the Middle East region handled by the Singapore hub.

Furthermore, for a given exporting country, the consolidated transport volume handled by the Singapore hub is calculated as the sum of its ammonia export volumes to all Asian importing countries. Taking Saudi Arabia as an example:

$$V_{SA\rightarrow SG} = V_{SA\rightarrow TH} + V_{SA\rightarrow KR} + V_{SA\rightarrow CN} + V_{SA\rightarrow OSEA}, \quad (32)$$

where TH, KR, CN, and OSEA denote Thailand, South Korea, China, and Other Southeast Asian countries, respectively.

The export volumes of Australia and China are treated using the same aggregation approach under the hub-and-spoke mode.

In addition to handling ammonia cargoes transshipped through the hub, the Singapore terminal is also assumed to process ammonia imports destined for domestic consumption (e.g., imports from Malaysia and Indonesia). Accordingly, the total annual throughput of the Singapore terminal consists of both transshipment flows and imports for domestic use, which can be expressed as:

$$V_{SG} = V_{ME\rightarrow SG} + V_{AU\rightarrow SG} + V_{CN\rightarrow SG} + V_{OTH\rightarrow SG}, \quad (33)$$

where V_{SG} represents the total annual ammonia volume handled by the Singapore terminal. $V_{OTH\rightarrow SG}$ indicates ammonia import for domestic consumption by Singapore.

During the distribution stage, the volume of ammonia delivered from the Singapore hub to each importing country is set equal to that country's observed annual ammonia imports from exporting regions such as the Middle East, Australia, and China. This assumption ensures that variations in the maritime shipping structure under the hub-and-spoke mode do not affect the overall trade scale of individual importing countries.

Taking Thailand as an example, the ammonia volume received via the Singapore hub under the hub-and-spoke mode is equal to the sum of its annual ammonia imports from the Middle East countries, Australia, and China:

$$V_{SG\rightarrow TH} = V_{ME\rightarrow TH} + V_{AU\rightarrow TH} + V_{CN\rightarrow TH} \quad (34)$$

The volumes for the remaining importing countries are determined using the same calculation approach.

Based on the above rules for transport volumes, this study subsequently determines the maritime transport distances and annual shipment volumes corresponding to each shipping route under the hub-and-spoke scenario.

5. Results

5.1. Overall comparison under the baseline scenario

In the base case analysis, transport costs are compared across 26 shipping routes. The results indicate 17 routes exhibit lower unit transport costs under the hub-and-spoke mode, accounting for over 65% of the total routes analyzed as shown in Figure 4. These findings show that, under certain combinations of shipment scale and transport distance, introducing a transshipment hub can yield economic benefits.

In 2023, Saudi Arabia was the largest exporter of ammonia to Asia, with total exporting volumes reaching approximately 1.8 Mt. Given its representative role in regional ammonia trade, routes originating from Saudi Arabia are selected as a case to illustrate the results above and compare cost performance across alternative maritime shipping modes. Among all, the Saudi Arabia-Thailand route (43320 t/annual) and the Saudi Arabia-Other Southeast Asian countries route (32242 t/annual) are characterized by relatively small annual shipment volumes. Under these conditions, the hub-and-spoke shipping mode demonstrates superior economic performance compared to direct shipping. For the Saudi Arabia-Thailand route, under direct shipping, the lowest transport cost is achieved using SGCs, at approximately 0.20 USD/ kgNH_3. Under the hub-and-spoke mode, however, a combination of LGCs for truck-haul transport and SGCs for feeder distribution (LGC + SGC) further reduces transport costs to 0.14 USD/ kgNH_3. Compared with direct shipping using LGCs, this combination yields a cost reduction of approximately 52.2%.

Similar cost patterns are observed for low-volume export routes from other Middle Eastern countries. For example, on the Qatar-Other Southeast Asian countries route, the hub-and-spoke mode also outperforms direct shipping in terms of transportation cost, further supporting the applicability of hub-based transport under small-scale demand conditions.

By contrast, for Saudi Arabia's export routes to South Korea (410350 t/annual) and China (181933 t/annual), the substantially larger shipment volumes make direct shipping economically more favorable. For the Saudi Arabia-South Korea route, direct shipping using LGCs achieves the lowest unit transport cost, at approximately 0.076 USD/kg NH_3. Under the hub-and-spoke mode, the most cost-efficient vessel combination is LGC + MGC, yielding a unit transport cost of 0.106 USD/kg NH_3, which remains higher than that of the direct shipping option.

Beyond Saudi Arabia, exporting countries such as Qatar, Oman, Australia, and China similarly exhibit trade structures characterized by one or more high-volume trunk export routes. Under these conditions, direct shipping along trunk routes fully exploits economies of scale, thereby limiting the potential for further cost reductions through hub-and-spoke transport mode. In comparison, for exporters such as the UAE and Bahrain, where overall export volumes are relatively small, and shipment volumes are more evenly distributed across routes, the hub-and-spoke mode is economically superior to direct shipping in most scenarios.

Overall, the results indicate that the cost reductions associated with the hub-and-spoke mode are primarily concentrated in low-volume route scenarios. For such routes, direct shipping often suffers from low vessel utilization, resulting in substantially higher unit transport costs. By consolidating shipments at a hub and redistributing them to destination countries, the hub-and-spoke method effectively mitigates scale disadvantages associated with insufficient shipment volumes, thereby generating clear economic benefits. It should be noted that these cost advantages do not arise from direct efficiency gains at individual shipping routes. Instead, they are driven by network-level aggregation, in which demand from low-volume routes is pooled with that from high-volume trunk routes. This aggregation enables the deployment of larger vessels on the trunk-haul segment, thereby diluting unit transport costs.

Furthermore, transport cost components are decomposed to reveal the mechanisms underlying the economic differences between hub-and-spoke and direct shipping modes.

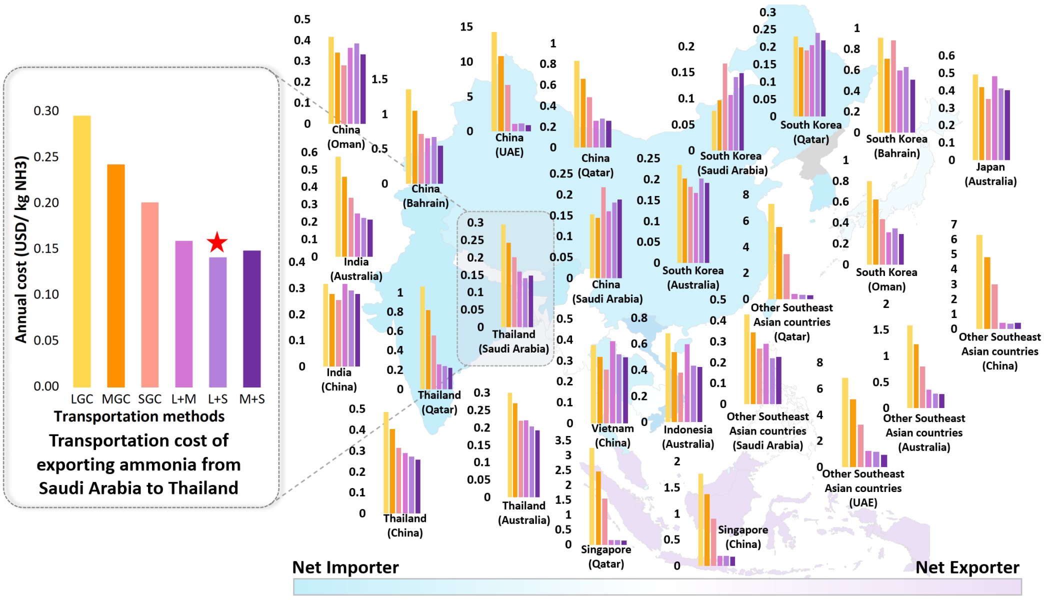


Figure. 4. *Comparison of transportation costs across different shipping routes and vessel size combinations under the direct and hub-and-spoke modes (bar heights indicate transportation costs; labels below bars denote importing countries and their corresponding exporting countries in parentheses).*

For the Saudi Arabia-Thailand route, a key feature of the hub-and-spoke mode is the substantial reduction in vessel CAPEX, as shown in Figure 5. For instance, compared with direct shipping using a single LGC, the hub-and-spoke mode employing an LGC + SGC combination reduces vessel CAPEX by approximately 76.7%.

Under the hub-and-spoke mode, large vessels are deployed for the consolidated transport segment between the Middle East and Singapore, enabling the full realization of economies of scale. This not only lowers vessel capital-related costs, but also reduces the number of voyages, thereby further decreasing labor, maintenance, and miscellaneous costs allocated per unit of transported ammonia along the trunk-haul segment. As a result, unit transport costs on the main haul are substantially reduced.

Meanwhile, given Thailand's relatively low import volume, deploying smaller vessels, such as MGCs or SGCs, on the Singapore-Thailand distribution segment better aligns vessel capacity with demand, improving economic performance in the second distribution transport stage.

Although the hub-and-spoke mode entails moderately higher port costs, primarily driven by increased port calls associated with smaller vessels, and also introduces additional hub-related capital and operating costs, these additional costs are outweighed by savings in vessel CAPEX and trunk-haul transport. Consequently, the hub-and-spoke mode still achieves a lower overall transport cost for this route.

By contrast, the Saudi Arabia-China route provides another case in Figure 6 for illustrating why the hub-and-spoke mode struggles to outperform direct shipping under high volume conditions. Compared with the Saudi Arabia-Thailand route, the substantially larger shipment volume along this route reduces the relative cost advantage of SGCs under direct shipping. Deploying SGCs would require at least 3 vessels (ε=2.46) to meet annual transport demand, thereby eroding their cost competitiveness.

As shipment volumes increase, MGCs and LGCs, owing to their larger single-vessel capacities, can exploit economies of scale more effectively. Consequently, under direct shipping, configurations employing MGCs or LGCs exhibit markedly lower unit transport costs than those relying on SGCs.

Under the hub-and-spoke mode, although costs along the Middle East-Singapore consolidated segment are minimized through demand aggregation, the large shipment volume required on the Singapore-China distribution segment results in a relatively higher volume adjustment factor, ε_B=1.29. This implies that, in practice, at least two SGCs are required to meet China's annual ammonia import demand from Saudi Arabia.

In addition, compared with direct shipping, the disadvantages of the hub-and-spoke configuration along this route are primarily reflected in non-CAPEX cost components associated with the increased number of small vessel voyages on the distribution segment. For example, under the MGC+SGC configuration, port-related costs are approximately 39% higher than those under direct shipping with MGCs, while fuel costs increase by about 61%.

Taken together, these factors explain why the hub-and-spoke shipping structure fails to achieve superior overall economic performance relative to direct shipping along the Saudi Arabia-China route.

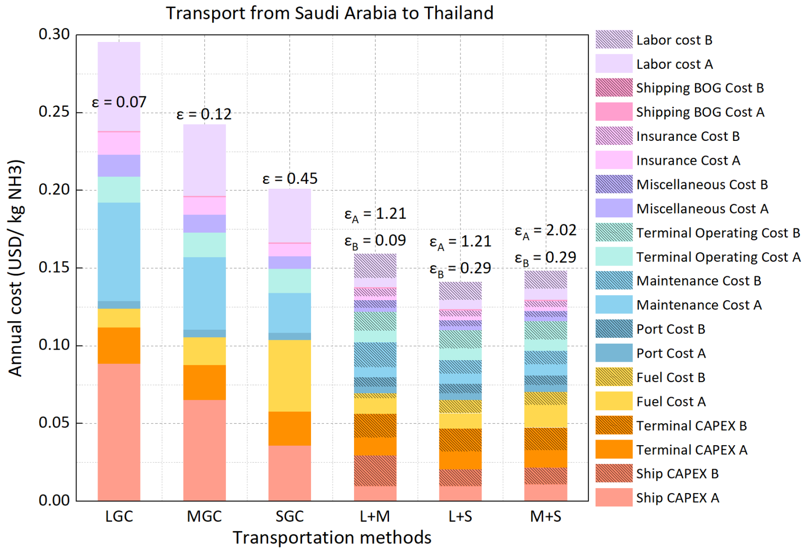


Figure. 5. *Detailed cost breakdown comparison between hub-and-spoke and direct shipping modes for the Saudi Arabia-Thailand route case.*

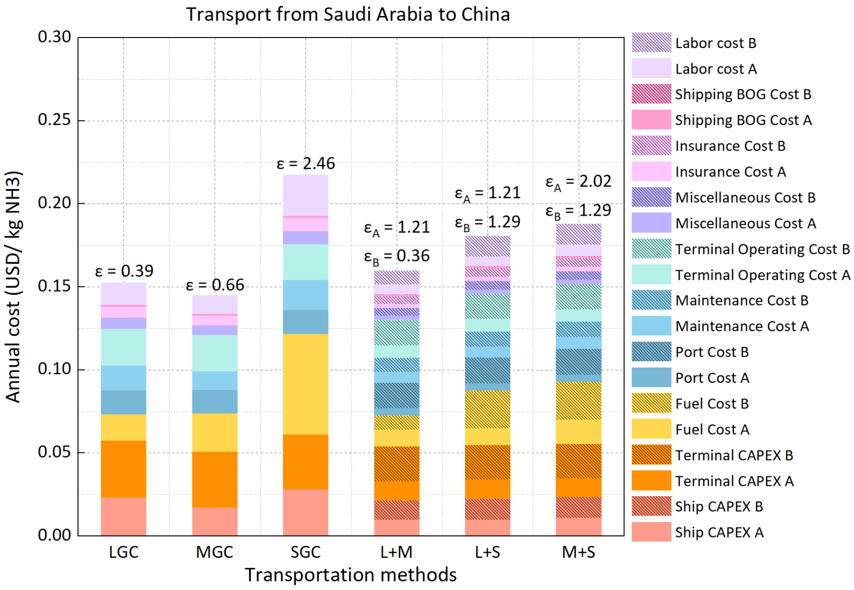


Figure. 6. *Detailed cost breakdown comparison between hub-and-spoke and direct shipping modes for the Saudi Arabia-China route case.*

5.2. Impact of shipment volumes on transportation costs

In the base case, ammonia demand in each importing country is assumed to be handled by a single port terminal. In practice, however, large importing countries typically distribute ammonia inflows across multiple ports, resulting in a more spatially distributed logistics structure. To capture this effect, an extended analysis is conducted for China and South Korea, two of the largest ammonia importers in Asia, using port-level disaggregation.

Based on China's customs statistics [23], ammonia imports from the Middle East are primarily handled by Shanghai, Jiangsu, and Henan. As Henan is an inland province, its import demand is proxied by ports in Jiangsu due to their geographical proximity. For South Korea, in the absence of detailed port-level data, this study assumes that two ports of comparable scale, Ulsan and Yeosu [5], share the national ammonia import volume equally. The resulting cost comparisons between the direct shipping and hub-and-spoke configurations are illustrated in Figure 7.

For China's import routes, the lowest transport costs under port-level disaggregation are consistently observed in the hub-and-spoke mode when realistic trade data are applied, in contrast to the baseline single-port assumption.

For South Korea, with the exception of the Saudi Arabia-South Korea route, where direct shipping still remains cost advantageous (indicated by triangular markers in Figure 7), the lowest transport costs for all other routes under the port disaggregated scenario are likewise achieved under the hub-and-spoke mode.

Under the baseline single-port assumption, the LGC+MGC combination in the hub-and-spoke mode from Qatar-South Korea route yields the lowest cost, yet remains approximately 7.4% higher than the direct shipping option using SGCs. Under the port-disaggregated scenario, however, focusing on the Ulsan port, the optimal hub-and-spoke mode achieves a cost reduction of approximately 16% relative to direct shipping.

The key mechanism underlying these shifts lies in the redistribution of shipment volumes across routes induced by port-level disaggregation in the real world. By fragmenting aggregate demand into smaller route-level flows, disaggregation reduces the effective shipment scale on individual routes, thereby weakening the economies of scale that underpin the cost advantage of direct shipping.

This effect is illustrated by the Saudi Arabia-China route. Under the single port assumption, the unit transport cost using MGCs is approximately 0.14 USD/kg NH_3. Under the port-disaggregated scenario, the corresponding cost increases to around 0.18-0.19 USD/kg NH_3 due to reduced shipment volumes. In comparison, the optimal hub-and-spoke mode exhibits a much smaller change, with cost increasing from approximately 0.16 USD/kg NH_3 to about 0.18 USD/kg NH_3.

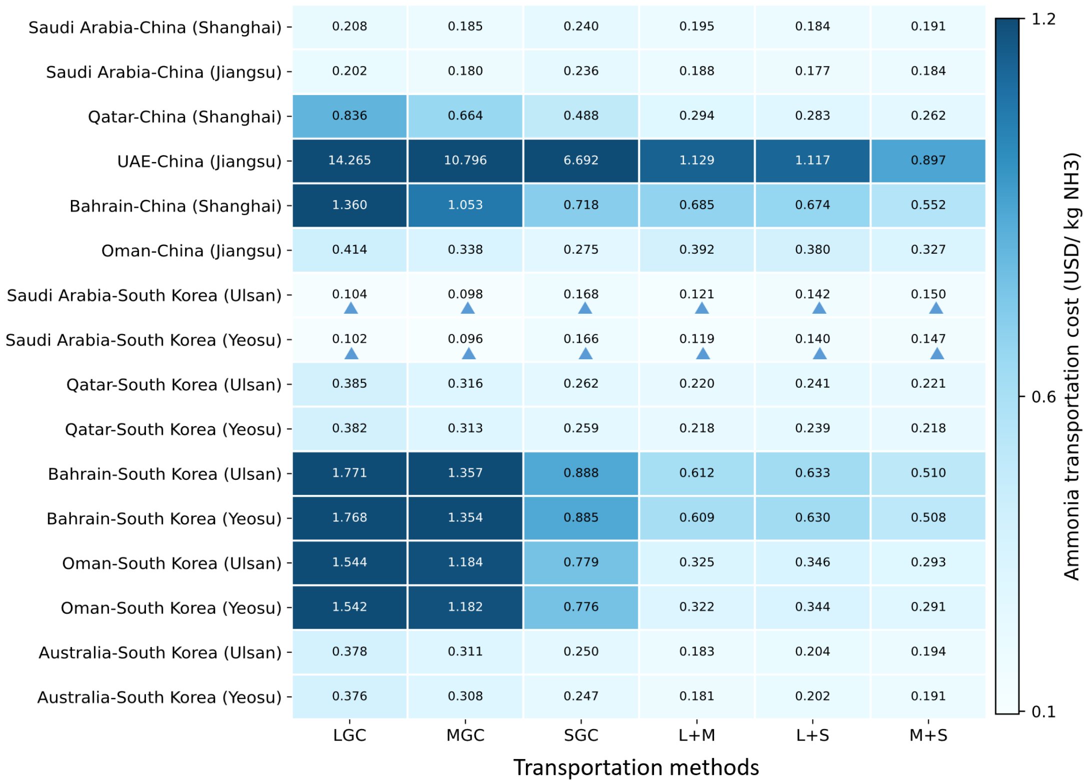


Figure 7. *Comparison of transportation costs under different shipping modes for ammonia import volumes in China and South Korea under a port-disaggregated scenario.*

6. Conclusion

Given the growing potential for cross-regional low-carbon ammonia trade, this study systematically examines the feasibility of introducing a hub-and-spoke maritime shipping mode to restructure transport systems and reduce ammonia shipping costs in Asia.

An ammonia maritime transport cost model is developed that relaxes the conventional full-load and single vessel assumptions by allowing fleet size to adjust endogenously in response to route-level shipment volumes. Using Singapore as a representative regional hub and incorporating observed trade characteristics in Asia, the model is applied to compare transport costs across shipping routes and modes quantitatively.

The main results are summarized as follows:

1. Overall, the hub-and-spoke maritime shipping mode can reduce unit transport costs under specific combinations of shipment volume and transport distance. Its economic advantages are primarily observed on routes with relatively low shipment volumes. Under such conditions, direct shipping suffers from low vessel utilization, leading to a substantial increase in unit transport costs.

2. The hub-and-spoke mode achieves cost advantages by enabling economies of scale on long-distance trunk routes, significantly reducing vessel CAPEX and per-unit costs. Meanwhile, using smaller vessels for regional distribution improves demand matching, thereby lowering overall transport costs. However, this advantage diminishes under high volume conditions, where direct shipping with larger vessels can more effectively exploit economies of scale and achieve lower unit transport costs. In contrast, the hub-and-spoke configuration requires additional small-vessel voyages in distribution, increasing non-CAPEX costs that ultimately outweigh the benefits of aggregation.

3. Considering the real-world conditions, geographical dispersion of port infrastructure may reduce effective shipment volumes on individual routes, thereby reinforcing the economic advantages of the hub-and-spoke mode.

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