Disruption of maritime trade chokepoints and the global LNG trade: An agent-based modeling approach

Abel Meza, Ibrahim Ari, Mohammed Al Sada, Muammer Koç

Maritime Transport Research 3 (2022) 100071

Contents lists available at ScienceDirect

Maritime Transport Research

journal homepage: www.sciencedirect.com/journal/maritime-transport-research

Disruption of maritime trade chokepoints and the global LNG trade: An agent-based modeling approach

Abel Meza *, Ibrahim Ari, Mohammed Al Sada, Muammer Koç *

Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar

ARTICLE INFO

Keywords:
LNG trade
Chokepoints disruption
Panama canal
Suez canal
Malacca strait
Agent-based model

ABSTRACT

Maritime chokepoints are key corridors in the global supply chain because they connect water-bodies, countries, and regions worldwide with few alternative routes. In case of closure (as the blockade of the Suez Canal in March 2021), the energy supply is substantially affected. Therefore, clear and safe passage through these chokepoints plays a critical role in energy transportation, global economy, and sustainable development. This study uses Agent-Based Modeling to develop an LNG market model and simulate the disruption of three main chokepoints: Panama Canal, Suez Canal / Bab el-Mandeb Strait, and Malacca Strait. After validating the computational model with the actual historical data, the model shows the chokepoints blockade effects on changing the LNG trade and exports from suppliers. The implications are immediate. In general, countries should work together to secure maritime trade routes, retain clear and safe maritime corridors, establish potential passages as alternatives to these chokepoints where possible, and decentralize LNG plants to have access from or to different maritime routes. Each importer should integrate their gas markets with pipelines networks, search for domestic gas resources, and diversify energy sources to decline energy dependency and gas imports from remote producing areas.

1. Introduction

On March 23, 2021, a huge container ship registered as Ever Given was crossing the Suez Canal, the only waterway connection between the Red and the Mediterranean Seas. This Canal is one of the busiest waterways, supporting high maritime traffic every day. However, that day, the Ever Given was about to make history because it provoked the most disastrous nautical incident in Suez: it wedged across the Canal, blocking it out completely (Lee and Wong, 2021).

The commercial disruption of the Canal lasted about one week until operators dislodged the ship (BBC, 2021a, 2021b), with no possibilities to bypass the incident site. This closure caused a high cost for the global maritime traffic because the Suez Canal is a unique waterway connecting Europe, Africa, and Asia. It is estimated that about 12% of the worldwide trade goes across the Canal (Brigham, 2021), including oil and gas tankers, with few substitutions to bypass any disruption. This example of blockade reminded us how critical some waterways, canals, and straits are for maritime trade and commercial activities at the global level.

That reminder is timely when global maritime trade has grown exponentially for decades, especially since World War II. Maritime trade plays a fundamental role in our global economy, and the availability of sea lanes is crucial. Into such lanes, some narrow passages

Abbreviations: NG, Natural Gas; LNG, Liquefied Natural Gas; ABM, Agent-Based Modeling; BEM, Bab el-Mandeb; BCM, Billion Cubic Meters; MTPA, Mega Tonnes Per Annum; AP, Asia Pacific.

* Corresponding authors.
E-mail addresses: amezatalavera@hbku.edu.qa (A. Meza), mkoc@hbku.edu.qa (M. Koç).

https://doi.org/10.1016/j.martra.2022.100071
Received 15 May 2022; Received in revised form 21 August 2022; Accepted 6 September 2022
Available online 21 September 2022

Table 1
Types of incidents affecting secure trade through chokepoints.

Incidents	Description	Examples
Operational	Simple incidents or serious operational accidents could cut out the commercial lanes. Operations are usually more effective and softer nowadays, but incidents are still a possibility.	The Ever Given incident (2021)
Weather/climate	Some chokepoints are located in tropical areas of climate disturbance. Others are in areas where unlikely, but potential weather events could lead to infrastructure damage, destruction, or closure	Panama Canal closure due to heavy rains (2010)
War, terrorist attacks, political instability, piracy, and others	Most of the chokepoints are located near developing countries with little control around seawaters or countries with a historical record of conflicts and attacks, aggravating these incidents.	Iran and the political/ diplomatic instability in Hormuz

are critical arteries to consider in maritime security, energy security, energy strategy, and supply (Von Hippel et al., 2011). As other authors (Funk, 2017; Miah et al., 2019; Rodrigue, 2004). In this study, we refer to these key passageways as "chokepoints".

Chokepoints play a crucial role when considering supply management for every commodity in our developed world, especially those commodities that are difficult to transport by land or air. That is the case of energy resources transported from remote world areas, across continents and oceans to reach markets and consumers. In the case of oil and natural gas (NG), land pipelines are helpful to connect production centers to markets in an extensive supply chain. Nevertheless, distances and geographical barriers such as rugged topography or massive water bodies (e.g., oceans and others) make pipelaying unfeasible and expensive. Maritime operations fill the gap for a massive transportation system across oceans. Since oil and natural gas supply the vital energy to move our commercial and economic activities day by day, any significant disruption could mean trouble in our economy. Chokepoints are the geographical risks that could disrupt the supply for military, political, or fortuitous reasons. Consequently, we can realize their growing strategic importance in a more connected and globalized world.

Further, we increasingly consume oil and gas since World War II. NG is the last of fossil fuels to be commercialized and the most difficult to transport. Pipelines were the first mean to transport NG; however, NG pipelines become unprofitable when distances are larger than 700 miles for sea and 2200 miles for land, due to the operative expenses to pump across such distances (Foss, 2012). Plus, just a few countries count with extensive, decentralized gas networks crossing countries' borders, like North America and Europe (Birol et al., 2011). Meanwhile, NG consumption expanded with time, making it necessary a more globalized and flexible medium. The LNG supply chain with the decentralized, global and maritime routes fills the market gap (Heidari and Weber, 2017).

NG is regarded as the transitionary energy resource between fossil fuels and renewable energies, reducing carbon emissions, equally affordable, abundant, and readily available (IEA, 2012; Tereshin et al., 2015). Thereby NG consumption may increase soon across the world. That creates an opportunity and a challenge to keep developing LNG infrastructure and the proper supply distribution network, into which the maritime chokepoints are fundamental. The challenge is augmented when we consider that, as with other fossil fuels, gas resources are concentrated in a few world regions, usually far away from the largest consumer markets. It is essential to count on a conflict-free, stable distribution network to secure the continuous flow of gas across seas and continents.

This work addresses how disruption of maritime chokepoints may affect the LNG trade, suppliers, and consumers, responding to questions such as a) what could be the effects of chokepoints disruption on the LNG market trade? b) What options could come to bridge the supply in case of disruptions? The LNG market and the disruptions in the supply chain are simulated using interacting agents, in a method called Agent-Based Modeling (ABM).

The following sections develop the research problem, the model, and the simulations; Section 2 provides definitions and background related to the chokepoints in the LNG maritime network and the suitable literature review of other works on the subject. Section 3 introduces Agent-Based Modeling as methodology and explains the simulation model we use for our work, the ABM LNG model. Section 4 provides data for the simulations, the modeled chokepoints, the scenarios and demonstrates the model's accuracy by validation against real data of LNG trade. Section 5 presents the simulation results in detail, while Section 6 elaborates the ensuing discussion around them, with implications from geopolitical, strategic, operational, and policy perspectives. Section 7 finishes the paper with conclusions and answers to the proposed questions.

2. Chokepoints, the LNG market, and initial studies

2.1. Chokepoints and their relevance

In general, a chokepoint is "a vulnerable point of congestion along a route" (Bailey and Wellesley, 2017). Referred to the maritime security trade, the Energy Information Agency (EIA) of the US defines chokepoints as "narrow channels along widely used global sea routes, some so narrow that restrictions regulate the size of the vessels that can navigate through them" (Kosai and Unesaki, 2016). We may define chokepoints as places where regular sea transit is limited due to their physical capacity and characteristics, but they cannot be easily bypassed because there are few alternatives (if any) and the other routes are way longer, leading to over costs and delays in the supply chain (Rodrigue, 2004). Chokepoints are the weakest links in our supply web. When they are broken or disrupted, logistic operations and the economic system suffer because multiple commercial activities rely on them, leading to shortages, potential economic crisis, and possibly other emergencies in a complicated chain reaction (Kitamura and Managi, 2017).

Maritime chokepoints have been critical since sea trade developed regionally and globally. As our world became more physically

Table 2
Profile and major features of chokepoints.

Chokepoint	Connecting	Bordering Countries	Type	Width	Affected by	Incidents
Strait of Hormuz	The Persian Gulf, Gulf of Oman, and the Indian Ocean	Iran, United Arab Emirates (UAE), and Oman	Natural - Strait	48 km	War Piracy Threat of terrorism	Tanker War (1984 – 1987)
Bab el-Mandeb	The Red Sea and the Arabian Sea	Eritrea, Somalia, Djibouti, and Yemen	Natural - Strait	32 km	Piracy Hijacking Terrorist attacks	USS Cole Attack (2000)
Suez Canal	The Mediterranean and the Red Sea	Egypt	Artificial –waterway	0.2 km	War Diplomatic disputes Operational incidents	Ever Given blockade (2021) Invasion of Sinai Peninsula Six Days War
Malacca Strait	The Indian Ocean, the South China Sea, and the Pacific Ocean	Indonesia, Singapore, and Malaysia	Natural - Strait	2.5 km	Diplomatic disputes Piracy Threat of terrorism	Orapin 4 piracy attack (2014)
Turkish Straits (Bosphorus and Dardanelles)	The Black Sea and the Mediterranean Sea	Turkey	Natural - Strait	1 km	Environmental issues	Constant pollution of Marmara Sea and straits due to heavy ships traffic
Panama Canal	The Atlantic and the Pacific Oceans	Panama	Artificial - Canal	0.3 km	Infrastructure dimensions, weather and climate	Panama Canal closure due to heavy rains (2010)
Gibraltar Strait	The Mediterranean Sea and the Atlantic Ocean	Spain, Gibraltar (UK), and Morocco	Natural - Strait	13 km	Weather and climate	Blockade by the Spanish Republican Navy (1936)

interconnected by commercial activities (i.e., since the Colonial European journeys), they started to gain more relevance. The 20th century provided a new level of strategic importance because human trade developed as never before. This time, the world depended on high-density energy resources like fossil fuels to supply economic activity. That made controlling the regular flow of energy across these chokepoints a matter of continued survival for entire nations (such critical dependence intensifies in times of war like the two World Wars). In the last decades, the control and normal flow of oil provided ground for diplomatic and military confrontation in some chokepoints and developed the conceptual risks and possible remedies to trade interruption. One example was the constant confrontation regarding control over the Suez Canal during the 1960s and 1970s (Feyrer, 2021).

Table 1 summarizes the types of incidents affecting the normal traffic of chokepoints (Bailey and Wellesley, 2017) and provides some examples of these incidents. Some of them are very recent like the Ever Given blockade; others are historical like the multiple threats and conflicts in the Strait of Hormuz related to the Iranian political instability:

Beyond these incidents interrupting the normal flow of commodities, some future trends potentially increase the operational risks around chokepoints. The first is that, as trade continues to grow, the importance of chokepoints, our dependence, and their cruciality as transit lanes would probably increase. The case with NG is significant because if the goal is to turn gas into the dominant fuel of the future, its secure commercial flow is a must.

The second is climate change. We have already stated how weather events could affect chokepoints operation. Further, climate change influences slowly but irreversible the sea levels, wear of related infrastructure, extreme weather events, and other hazards that pressure our energy demands, i.e., our need for more congested supply lanes. This causality is not just one way. With extreme weather affecting sea lanes and passageways, conflicts to get more supplies would increase demand, operation, and restrictions around chokepoints. This trend could intensify the disputes and political instability in the neighboring countries to these passageways. In short, climate change may trigger instability in different levels, stressing operations and security around chokepoints.

We can add a third trend: the escalation on war and political instability. With more intensive maritime trade, increasing climate change, or even independently of these trends, security among chokepoints is far from granted. In the last years, we are watching an increase of conflicts that may finish to affect the security on different maritime routes. For instance, the Ukrainian – Russian war (Fulwood et al., 2022) may add new struggles regarding maritime trade on countries under conflict and their allies, especially when we consider Russia, the European countries, the US, China and other countries are all big players on the LNG industry, either exporters or importers. The possibilities of trade bans, trade restrictions and other mechanisms to penalize other countries may lead to more strain on some trading routes and chokepoints.

2.2. Major chokepoints and their profile

Chokepoints can be classified by their origin. Initially, they were only geographically narrow occurrences like straits or channels separating islands or continental territories in some locations. Nevertheless, human ingenuity built artificial waterways to connect waterbodies separated by a few kilometers, which may decisively cut more considerable traveling distances and times. Table 2 identifies the main chokepoints and their features (Miah et al., 2019; Narula, 2019; Rodrigue, 2004).

Chokepoints can be easily defined by their physical features such as width, depth, length, which are the more salient characteristics. However, their commercial use leads us to identify more features, like usage, limited by physical attributes but increased by geographical and strategic importance. As the name indicates, a “chokepoint” limits the usage and maritime traffic, making it more

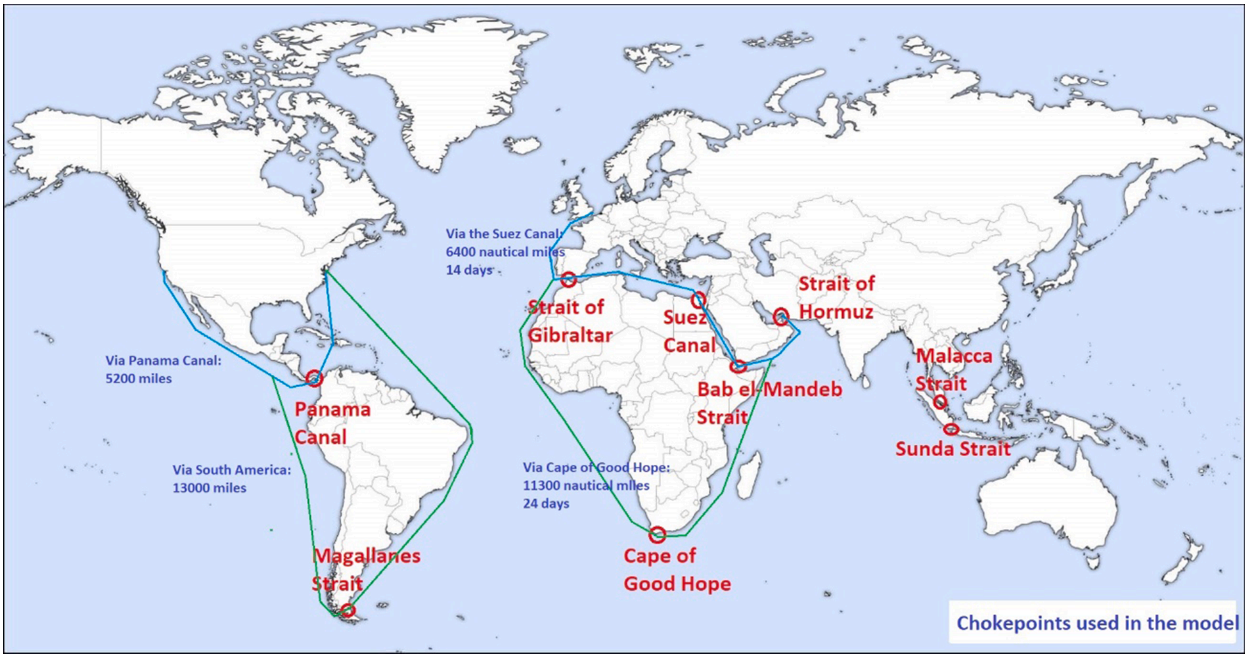

Fig. 1. Chokepoints include in the model.

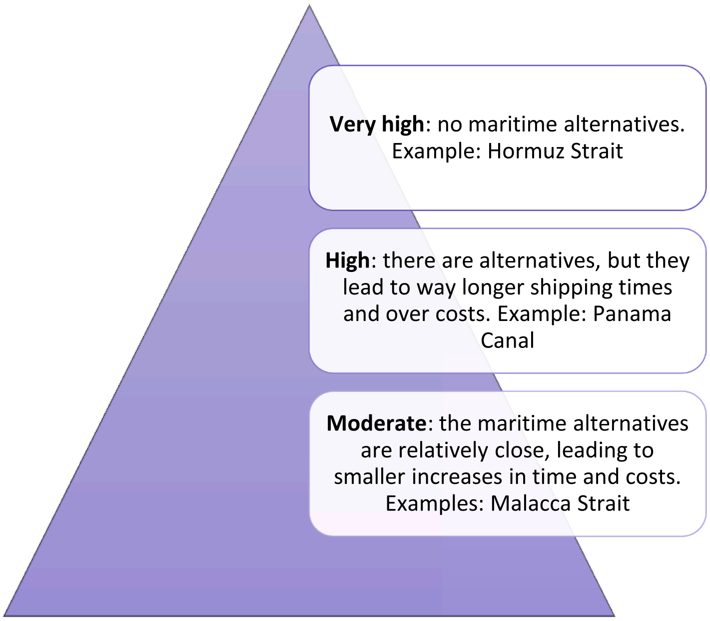

Fig. 2. Levels of the criticality of chokepoints.

valuable. Finally, chokepoints are identified by their access, i.e., whether control over the waterways leading to them is granted or not. Such control is related to agreements granting access permission and settling disputes, as commonly arise in decisive commercial routes.

From Table 2, we can see that many of the chokepoints are surrounded by developing countries or territories under constant conflict or international issues. However, their connection is precious since they save thousands of kilometers like the Suez Canal or the Panama Canal as in Fig. 1. Finally, it is relevant to classify the chokepoints according to their criticality. Criticality refers to how serious any incident in these spots could turn and its potential impact on the trade. As to the LNG trade and based on (Bailey and Wellesley, 2017), Fig. 2 shows the criticality:

2.3. Literature review

Chokepoints have been the subject of different studies and reports in the last years because of their maritime operations risks. Chatham House published a comprehensive assessment of the global food trade's concerns, risks, and vulnerabilities crossing the major maritime chokepoints (Bailey and Wellesley, 2017), very useful to understand the relevance when applied to the energy world. The importance of chokepoints in the energy world is described in several works. Rodrigue (2004) provides a complete description of how these junctures influence the flow of oil and the strategic impacts on future energy crises and oil shortages. Similarly (Miah et al., 2019), provide a more updated analysis of the geostrategic importance of the chokes and some alternatives to them regarding the regular flow of oil. Further, (Narula, 2019) elaborates on maritime security's role in protecting energy trade and global sustainable energy security, analyzing elements of the marine energy trade such as chokepoints, ports, and others concluding with suggestions on the security of ships.

Risk assessment of the chokepoints is one of the common subjects in the spotlight. Dimitroff (2014) analyzes several risks of cross-border pipelines and chokepoints, making a parallel between these two ways of oil and gas transportation, following an international law frame. From the maritime security point (Kosai and Unesaki, 2016), conceptualize the energy transportation security and then develop indicators to estimate the risks from piracy, chokepoints, and piracy for different shipping routes.

Particular cases of chokepoints disrupted by different incidents are topics for many papers. Malacca, the South East Asian straits and maritime lanes attract several articles regarding their importance for Chinese trade. Zhang (2011) sets the strategic landscape by describing the "Malacca dilemma" and the importance of that strait for Chinese energy imports (Leung, 2011; Zhang, 2011), asserting concerns and efforts to increase the Chinese influence in the region. Gong and Lu (2018) parametrize and quantify indicators on security assessment for the Maritime Silk Road from China to Europe, including Malacca and the Red Sea Straits. Even when there are many risks regarding the South East Asia region security (Graham, 2015), concludes on the robustness of the safety of maritime shipments and how the energy flow trades are evolving due to demand/supply dynamics.

Interruption of chokepoints uses different methodologies in the literature. Funk et al. (Alderson et al., 2020; Funk, 2017) analyzed the maritime sea transportation system and its resilience using a multilayered network theory and then applied multicommodity linear programming to optimize the system. These works aimed to investigate the interruption of some "weak" nodes of the system, i.e., chokepoints and containers port. Regarding trade interruption, the Suez Canal and the BEM Strait are the most studied passageways. Feyrer (2021) used a gravity model to identify the effect of the closure of the Suez Canal between 1967 and 1975, investigating the influence of distance on trade and trade on income. Bendall (2010) measured piracy costs from the perspective of shipping companies by taking a cost approach comparing the journey time. Meanwhile, (Fu et al., 2010) modeled the global economic development losses and shipping inefficiencies from the Somalian piracy around BEM Strait using an economic model.

About energy trade and chokepoints closures, CNA studies (Komiss and Huntzinger, 2011) prepared an in-depth report about the disruption of chokepoints, their repercussions on the maritime oil flow, and the economic effects. They followed economic methodologies (Input – Output estimations, Keynesian analysis) to estimate the effects on the economies of different countries. They found that some of the world's industrialized economies would enter into a sudden recession if the disruptions affected the oil flow for long and other countries do not share their strategic reserves of oil.

These are the studies regarding chokepoints disruption and the energy trade. As we might conclude, their scope is oil interruption and related effects. There are no studies reflecting the closure or disruption of maritime chokepoints on the LNG trade and no studies using Agent-Based Modeling as the methodology to study those events. The following section explains the advantages of ABM, the model we use to simulate disruptions and fill the literature gap.

3. Methodology: agent-based modeling (ABM) and model description

Agent-Based Modeling (ABM) is a simulation technique that represents the interactions between sets of autonomous elements (agents) under different conditions and restrictions in a particular environment influencing their behavior. According to modeling settings, the agents are heterogeneous elements or individuals who interact, take actions, make decisions, influence behaviors, and even adapt and learn from the past in different situations. They interact in ways that are difficult to predict, giving way to emerging behavior patterns. These characteristics are familiar to complex systems making ABM a tool to simulate complex systems and dynamics (Willenski and Rand, 2015).

We choose ABM to model the LNG market because the LNG market is a complex system with multiple agents. We may find tens of exporters and importers, hundreds of contracts, and thousands of cargoes every year. The balance between exporters and importers is constantly under pressure with boom and bust periods, new reserves and resources in some places while reserves depletion in others. There are unexpected new entrants and more robust competitors (Meza et al., 2022), together with new importers, new technologies, and market trends, but periods of crises and low prices, turning the panorama complicated (Corbeau and Ledesma, 2016; Meza and Koç, 2021). ABM could simulate the LNG trade and interactions under different scenarios, providing new insights and forecasts.

3.1. Model description

ABM is coded using different software; for this work, we employ AnyLogic® version 8.7 (AnyLogic Company, 2021). It is used by many companies and universities, featured with numerous examples of academic works (Ari and Koc, 2021; 2019; Feng, 2018; Muravev et al., 2021) and reviews, comparing it to other ABM tools (Abar et al., 2017).

AnyLogic® works with Geographical Information Systems (GIS) (Heppenstall et al., 2012) in the environment to place all the

Fig. 3. ABM map representation in AnyLogic.

Table 3
Agents and their symbols in Fig. 3.

Symbols	Agents' description
	Orange icons represent the liquefaction plants
	Light blue spheres are the regasification terminals
	Magenta triangles are the chokepoints
	Violet ships running along the maritime routes are the tankers

agents in any predetermined location, i.e., a province, a country, a region, a continent, or even the entire world. This feature helps us to place the agents in the LNG market at their different locations, connected by the commercial spatial sea routes worldwide, and then to simulate the LNG trade with the LNG ships and shipments running across the oceans and along the maritime routes (see Fig. 3 and Table 3).

The model representation emulates the LNG value chain from the production of NG and LNG on the exporters' side to the importers' side, where customers re-gasify the LNG shipments to be used according to their demand. The agents are the players, the cargoes, and the chokepoints in the LNG market, distributed geographically in regional markets, from where they shape the trade based on their constraints, needs, and under the rules of supply/demand. The model may also reflect the temporal evolution of the market following increasing demand, supply capacity, and trade, generating the LNG traded quantities per time step (days) and accumulated according to the statistical needs (months and years). The simulations reproduce the LNG export portfolios, import portfolios, and choices (diversification) through time, depending on the trade and agents' transactions. Fig. 4 represents the model with the agents, constant, variables, and functions, showing how the model characterizes the LNG market supply chain. This model was described and used to generate future scenarios of LNG competitiveness (Meza et al., 2021).

The most significant part of the disruption, the environment, is represented worldwide with the GIS map and maritime trade routes laid into the map (Fig. 3).

3.2. Description of agents

The agents we are using in the model are in Table 4. The geographical regions of Exporters and Importers are in Table 5; the chokepoints included are in Tables 3 and 4.

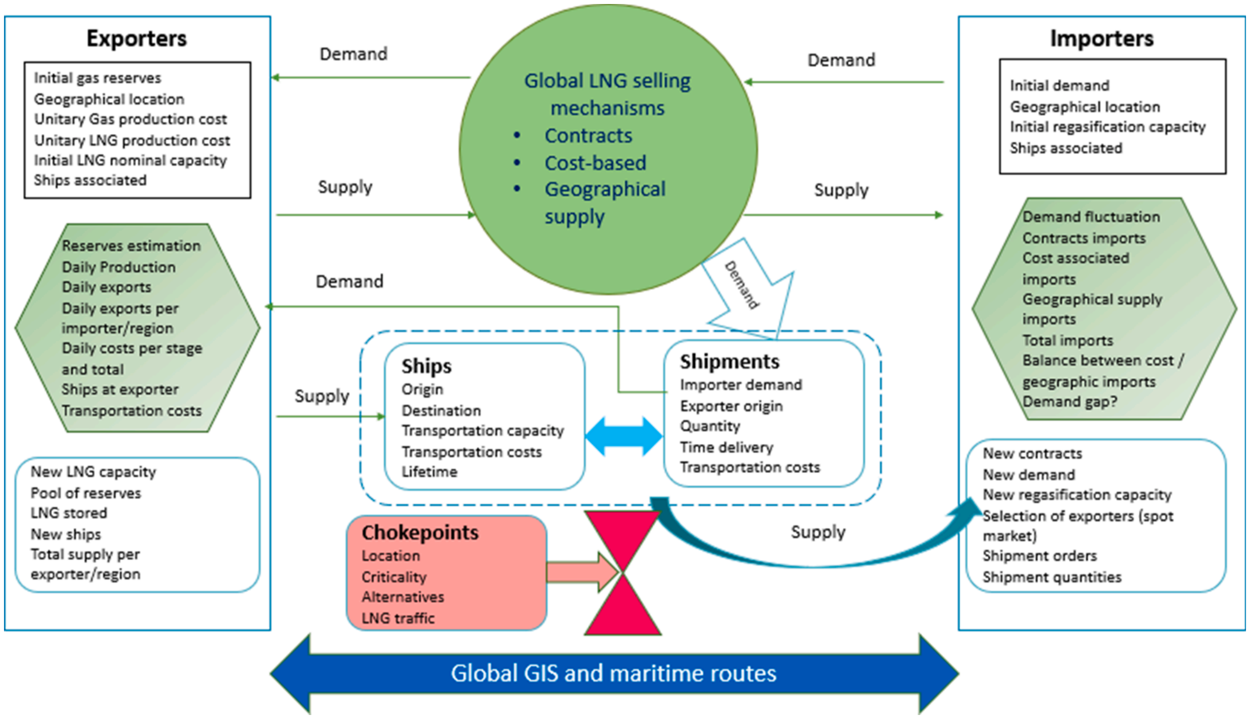

Fig. 4. Model Conceptualization of the LNG market with agents, mechanisms, and other features.

Table 4
Agents description.

Agents	Description
Exporters	They are the producers of LNG, each represented by one country, i.e., only one LNG production plant per country with diverse attributes. Their number may change with time; currently, we are assuming 21 exporters enumerated in Table 5.
Importers	Also represented as countries ordering LNG shipments according to their demand. There is just one importer/regasification facility per country and initially 30 importers to start with the simulation, but their number may change with time; they are enumerated in Table 5.
Ships	The LNG transporters circulating in a tailor-made global LNG network across all the oceans. They come in a fleet distributed geographically for the different exporters according to their size of exports capacity.
Shipments	The cargoes of LNG ordered from the importer, depending on the sales mechanisms to interact with the sellers and constrained by the demand, ships availability, etc.
Contracts	Passive agents who set up liable and contractual agreements for ordering shipments according to predetermined terms.
Chokepoints	Also passive agents which are located in every chokepoint and passageway for the LNG maritime network. They could restrict routes and stop the ships and shipments movements. They are listed in Table 6.

Table 5
Exporting and Importers represented in the model and regional division.

Region	Exporting countries	Importing countries
Middle East	Qatar, UAE, Oman	Israel, UAE, Kuwait
Asia Pacific	Australia, Papua New Guinea, Malaysia, Brunei	China, Japan, South Korea, Taiwan
South Asia	Indonesia	India, Bangladesh, Pakistan, Singapore, Thailand
North America	USA	Canada, Mexico
Latin America	Peru, Argentina, Trinidad & Tobago	Colombia, Argentina, Brazil, Chile
Europe	Norway	United Kingdom, France, Spain, Italy, Portugal, Belgium, Greece, Netherlands, Lithuania, Poland, Portugal, Turkey
Russia	Russia	N/A
North Africa	Egypt, Libya, Algeria	N/A
Africa	Cameroon, Equatorial Guinea, Nigeria, Angola.	N/A

Table 6
Chokepoints and passages included in the model.

Chokepoints and passages included in the model	Type	Location. Between
Hormuz Strait	Chokepoint	The Persian Gulf and the Indian Ocean
Bab el-Mandeb Strait	Chokepoint	The Red Sea and the Arabian Sea
Suez Canal	Chokepoint	The Red Sea and the Mediterranean Sea
Panama Canal	Chokepoint	The Atlantic and the Pacific Ocean
Malacca Strait	Chokepoint	The Indian Ocean and the South China Sea
Sunda Strait	Chokepoint	The Indian Ocean and Indonesian Sea
Gibraltar Strait	Chokepoint	The Atlantic Ocean and the Mediterranean Sea
Cape of Good Hope	Passage	The Indian and the Atlantic Ocean
Magallanes Strait	Passage	The Pacific and the Atlantic Ocean

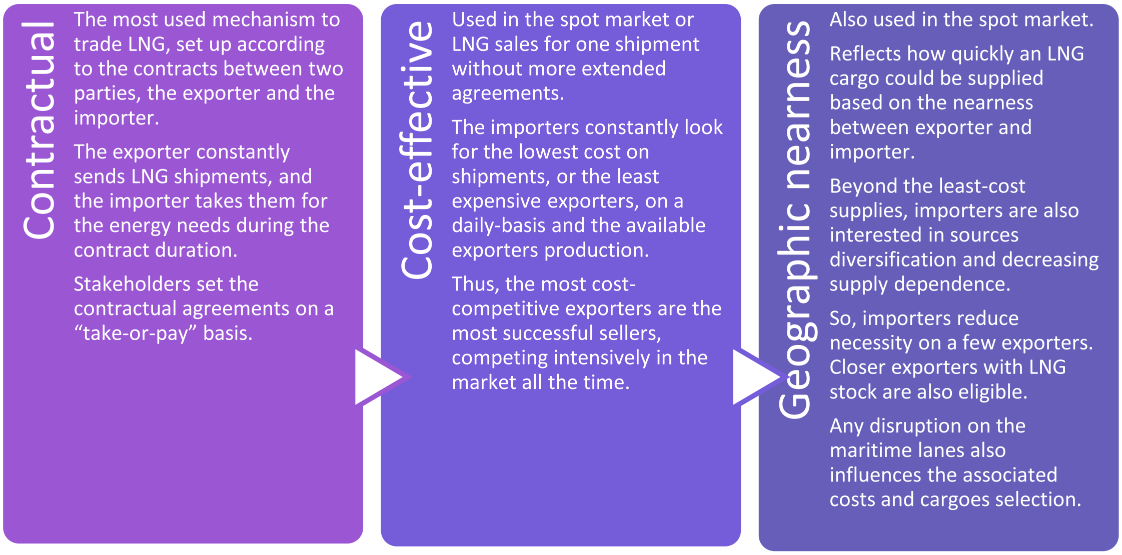

Fig. 5. Model mechanisms to trade LNG.

3.3. Model logic mechanism

The model works by trading cargoes of LNG between exporters and importers according to the mechanisms in Fig. 5.

The importers select their LNG supply based on these rules and market conditions. The following Eqs. (1), (2), (3) and (4) rule the cost-based mechanism.

$$Gas\ Production_{expenses} = Unitary\ Gas\ Production_{costs} * Gas\ Produced \tag{1}$$

$$LNG\ Production_{expenses} = Unitary\ LNG\ Production_{costs} * Gas\ Produced \tag{2}$$

$$Shipping_{expenses} = Shipping\ rate_{costs} * Shipping\ time \tag{3}$$

$$Exporter_{chosen} = Available\ Exporters\ (Least\ cost\ Exporter) \tag{4}$$

The geographical-nearness mechanism is below in Eq. (5).

$$Exporter_{chosen} = Available\ Exporters\ (Geographically\ closest\ Exporter) \tag{5}$$

3.4. Assumptions

The assumptions relative to the model and the maritime trade are as follows.

- All the exporters and importers are represented as one per country, i.e., there is one liquefaction plant and shipping facility per exporter country and one regasification plant and reception facility per importer country. This assumption helps to simplify the geographical settings of GIS configuration and reduce the need for additional data. Russia is the only exception due to the great extension of territory and long distance between its two LNG production plants located in the different continental regions.

Table 7
Parameters of exporters.

Parameters	Significance
Location	Indicates the geographical position of the exporter from where the ships and cargoes are sent. It also defines the exporter market and the closeness to the importers' markets
Initial Reserves	They are the reserves with which every exporter starts the simulation, depending on the year of start
Initial Liquefaction Capacity	Initial capacity to process and to liquefy LNG per country in MTPA. It is a production constraint per year, but it may change depending on the year and new LNG projects
Unitary Gas Production Costs	Cost of producing natural gas per unit of production, usually measured in $/MMBTU. It varies from exporter to exporter depending on reserves characteristics, production features, presence of near gas infrastructure, production location, among other aspects
Unitary LNG Production Costs	Cost of producing LNG per unit of production in the processing and liquefaction facilities. It includes the capital expenses (CAPEX) of building and commissioning the LNG cryogenic trains and operational costs (OPEX) of keeping up the LNG operations.

Table 8
Parameters of importers.

Parameters	Significance
Location	It indicates the geographical position of the country's importer or destination of the ships and cargoes go. It also defines the importer market and the closeness/routes from the exporters' markets
Initial Demand	The demand with which the importer starts importing at the base year of modeling
Initial Regasification Capacity	It is the initial capacity to re-gasify LNG per country importer, measured in MTPA. It is the constraint for demand, and it may change with time.
Region	The region to which the importer belongs

- Every exporter has an associated LNG ships' fleet to transport the gas shipments to the importers' destinations. The ships deliver the cargo and return to their exporter market, waiting to load new cargoes.
- All the ships travel at a constant speed of 10 m/*sec* or around 19 knots, a standard speed for LNG tankers.
- Distances are estimated based on the GIS routes built on the global map of the model, resembling the international shipping network routes.
- The exporters constantly revamp their shipping units. Ships come in just one average size of 170 000 m^3 or roughly 72,000 tonnes of LNG.
- Contractual engagements are the priority to satisfy the exporters based on the contract's commitments and sales. Any surplus in production is traded through the spot market.
- The model is not considering monthly demand differences due to seasonal needs.
- The chokepoints disruption takes place in the present time, 2021, with demand and supply conditions resembling the current LNG market.

3.5. Parameters, variables, and constraints

The main parameters of exporter and importer agent are *location, initial reserves, initial liquefaction capacity, unitary gas production cost, unitary* LNG *production cost, initial demand, initial regasification capacity, region,* as described in Tables 7 and 8 and presented with values in Tables A-1 and A-2 on the Appendix.

The main variables in the model are: the demand for every importer i, the supply capacity of the exporters e, that changes for the market depending on projects and time t, and the regasification capacity in the importers, with similar changes as the supply capacity. They work under the following Eqs. (6), (7), (8), (9) and (10)

$$Liquefaction\ Cap_{e,t+1} = Liquefaction\ Cap_{e,t} + New\ Liquefaction\ Cap_{e,t+1} \tag{6}$$

$$\sum_{i=1}^{m} Supply_{e\rightarrow i,t} \leq 1.1 * Liquefaction\ Capacity_{e,t}\ \forall\ t \tag{7}$$

where e and t represent exporters and time, respectively.

The model introduces the 1.1 factor for every exporter supplying the market because some exporters can export more than their nominal reported liquefaction capacity in some years

$$Regasification\ Cap_{i,t+1} = Regasification\ Cap_{i,t} + New\ Regas\ Cap_{i,t+1} \tag{8}$$

$$Demand_{i,t} \leq Regasification\ Capacity_{i,t} \tag{9}$$

where i corresponds importers, and t is time.

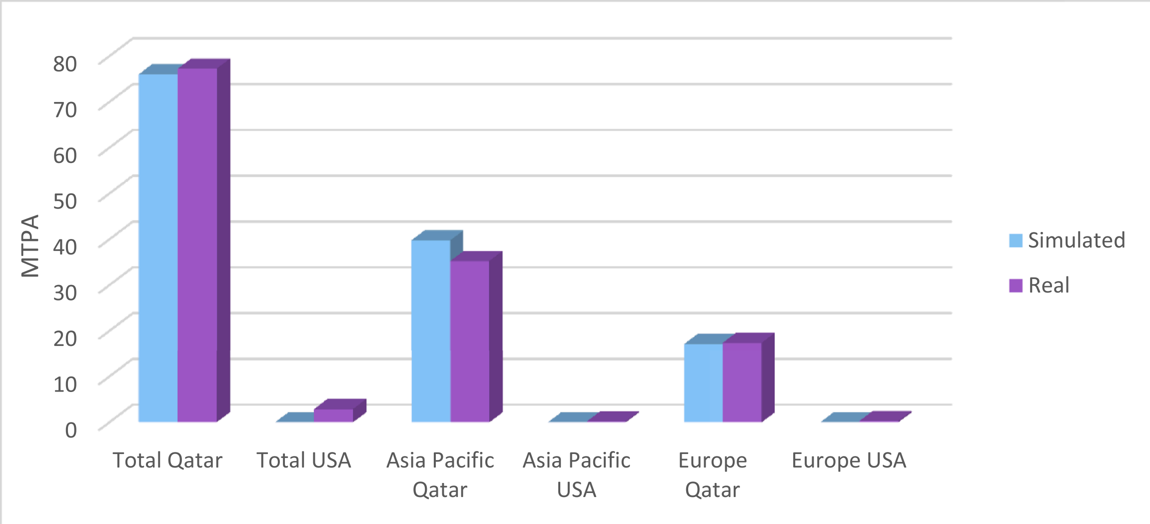

Fig. 6. Comparison of LNG Exports for Qatar and USA between simulation and real data (2016).

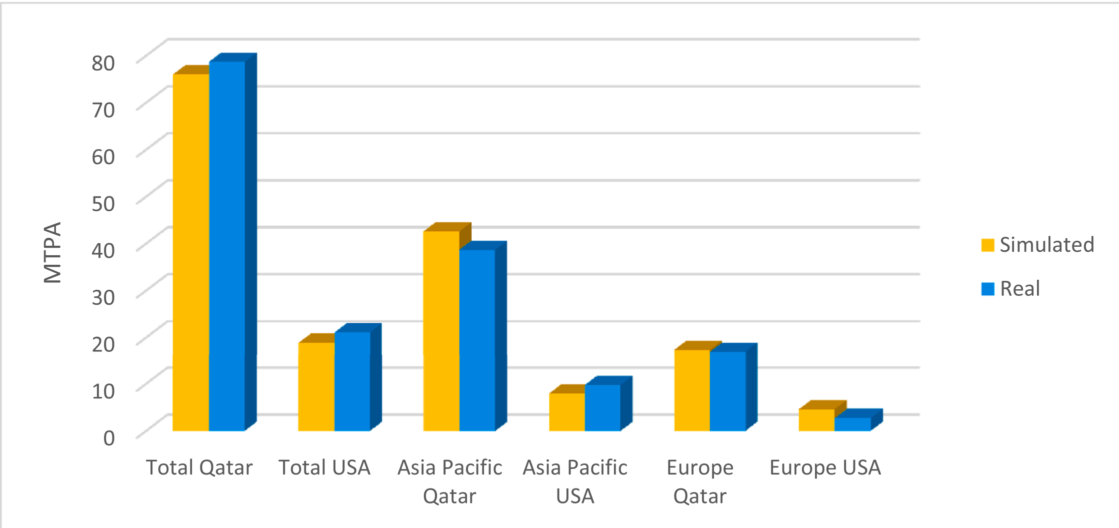

Fig. 7. Comparison of LNG Exports for Qatar and USA between simulation and real data (2018).

The trade with every importer i and exporters e in a time step t is given by the sum of LNG supplied to importer i from all the exporters e trading with i according to the demand of i as follows in Eq. (10).

$$Demand_{i,t} \geq \sum_{e=1}^{n} Supply_{e \rightarrow i,t} \ \forall \ t \tag{10}$$

4. Data and validation

This section proposes to test the model's accuracy by comparing its results with previous years and transit through the chokepoints. We could develop LNG trade projections and scenarios based on the accuracy of recalling the past LNG trade.

4.1. Data

We collected data from different sources. General data about infrastructure capacity comes from annual reports like the IGU World LNG reports (International Gas Union, 2021, 2020; IGU. 2019, 2018); data about LNG trade, supply, and demand are from the IGU (International Gas Union, 2021) and British Petroleum (BP, 2020). The Data Documentation report from DIW (Neumann et al., 2015)

Table 9
LNG traffic across chokepoints - real vs. simulated data – units MTPA.

Chokepoint / LNG traffic in MTPA	Real LNG traffic (2014)	Simulated LNG traffic (2014)	Real LNG traffic (2016)	Simulated LNG traffic (2016)
Hormuz Strait	81	83.74	87.45	85.10
Malacca Strait	84.2	79.85	65.7	58.68
Panama Canal	0[1]	0	NA	4.90
Suez Canal	24.64	21.82	24.64	22.25

[1] The data registers 0 MTPA in 2014 through the Panama Canal because the Panama Canal was open for other commodities but not for LNG trade. Accordingly, the simulation for that year uses every other route but no the Panama Canal for the LNG tankers.

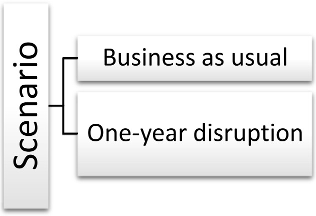

Fig. 8. Modeling scenarios.

presents a good summary of LNG contracts. Information comes from different sources about unitary costs for gas production, LNG production, and shipping costs (Corbeau and Ledesma, 2016; Kilisek, 2014; Ledesma et al., 2014; Steuer, 2019; U.S.Department of Energy, 2018). About LNG transit across the chokepoints, reports provided some scattered information (Energy Information Agency, 2017; Kimura et al., 2015)

4.2. Validation

The ABM LNG model is validated by showing its accuracy simulating the LNG exports from Qatar and the US to the Asian Pacific market, the European market, and their total global exports. These results were compared with the real data of 2016 and 2018 in Figs. 6 and 7. We choose these two exporters because they are two of the most important exporters and heavily affected by any closure of the chokepoints. Likewise, we choose to show the total exports because they are a measure of how much every exporter may allocate in the LNG market. Meanwhile, we display the exports to Asia Pacific and Europe because they are the two most relevant importing markets. The results show the similarities between simulations and the actual trade of these two years. The IGU annual reports published in 2017 and 2019 (I. International Gas Union, 2019, 2017) provided the factual data for comparison.

As to Fig. 6- year 2016, the model sets almost no exports from the USA because one of the assumptions is that any new liquefaction capacity commissioned in any year is included at the beginning of the next year. In 2016, the US started is long race to join the LNG exporters, with few plants and very small exports, both in total and to any LNG market. As to the case of Qatar, the model captures the relevance of this country as the top LNG exporter, with large shipments both to the Asian Pacific and European customers, based on the contracts of that year and spot sales.

Fig. 7– 2018 is different because the US have grown largely by then, with much more capacity able to allocate shipments in Europe and the US. Qatar keeps exporting at similar quantities, because it did not expand its liquefaction capacity and it was still the top exporter in 2018. The difference between real and simulated quantities is not large, reflecting that the model captures the exporting quantities both in aggregated and disaggregated amounts with fair accuracy.

Another step in the model validation was by comparing the real LNG traffic across the chokepoints against the simulated traffic in years where we have real data of LNG traffic through the chokepoints (Energy Information Agency, 2017; Kimura et al., 2015). Unlike maritime oil traffic, actual data of LNG traffic across chokepoints is scarce. Table 9 makes the comparison between simulations and reality.

Hormuz and Malacca Strait do not show significant differences in the comparison. The difference between real and simulated traffic in the Malacca Strait is probably larger because the simulations are not incorporating some small LNG players in the region, like Indonesia and Malaysia acting as importers in the Asian markets. Meanwhile there are fewer players interacting in the Strait of Hormuz LNG traffic, but they are all present in the simulations.

In the simulations, the Panama Canal had no LNG traffic in 2014 because the Panama was closed for LNG tankers in that year. As of 2016 – 2017, the Panama Canal opened the LNG traffic (The Maritime Executive, 2017) and the flow grew because the US and other exporters started shipping out more LNG cargo yearly. On the side of the Suez Canal, the differences are minor as well. However, since 2017, the US and Russia have added increasing exports traveling across the Suez route, making the present LNG traffic way larger.

4.3. Chokepoints and scenarios

We work modeling three chokepoints transit and their disruption effects:

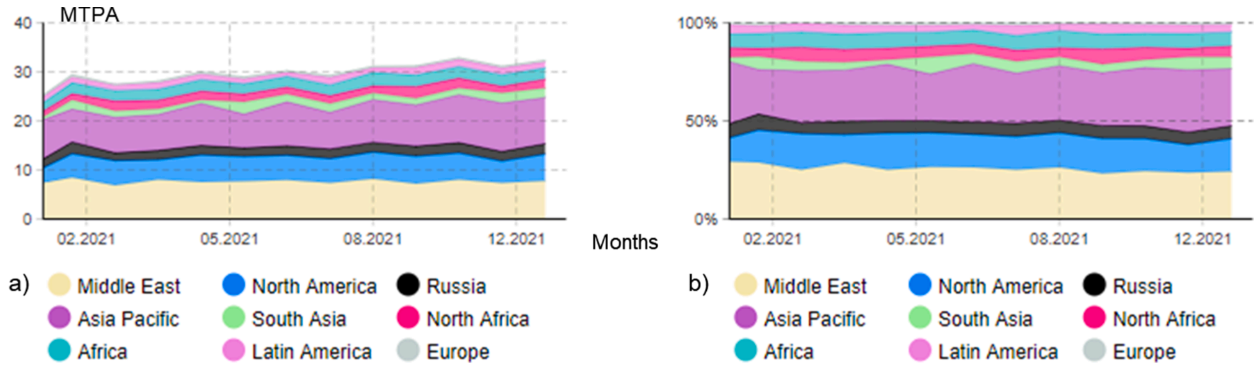

Fig. 9. Base case - LNG Exports origin regions a) per month in MTPA b) shares per month.

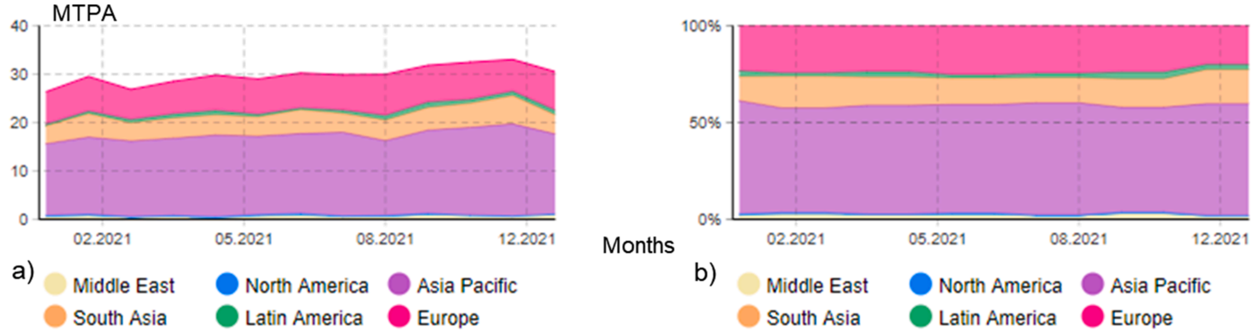

Fig. 10. Base case - LNG Imports destination regions a) per month in MTPA b) shares per month.

Table 10
LNG flow per chokepoint and case scenario in MTPA.

LNG flow per Strait / Canal and scenario	Base Case	Panama Cut	Suez/BEM cut	Malacca cut
Hormuz	88.92	88.49	87.84	86.54
Suez	55.94	84.17	0.00	54.50
Bab el-Mandeb	55.51	83.09	0.00	53.86
Malacca	65.23	90.65	53.71	0.00
Sunda	10.94	12.38	15.34	77.40
Gibraltar	70.63	95.26	44.50	70.06
Panama	35.57	0.00	38.88	36.86
Good Hope	14.47	15.34	62.93	15.41
Magallanes	1.58	5.33	0.94	0.79

1 Panama Canal
2 Bab el-Mandeb Strait and Suez Canal
3 Strait of Malacca

We choose these three chokepoints because they are essential in connecting different oceans and seas, with potential disruptions and interruptions anytime. However, they also show some alternatives from maritime and energy trade perspectives.

We prepared the base case plus one disruption scenario per chokepoint - Fig. 8:

The first scenario is the regular LNG traffic running along the sea lanes and chokepoints with no more restrictions than the market constraints and using the fastest routes to decrease costs. The second scenario is more complicated, involving a one-year closure of each proposed chokepoint due to war, dispute, or some extreme climatic event destroying the waterway. In this case, the chokepoint and the passages leading to it are no longer used, and other passageways have to be transited, leading to longer shipping times.

5. Results

We present first the base case scenario and then the disruption of the chokepoints

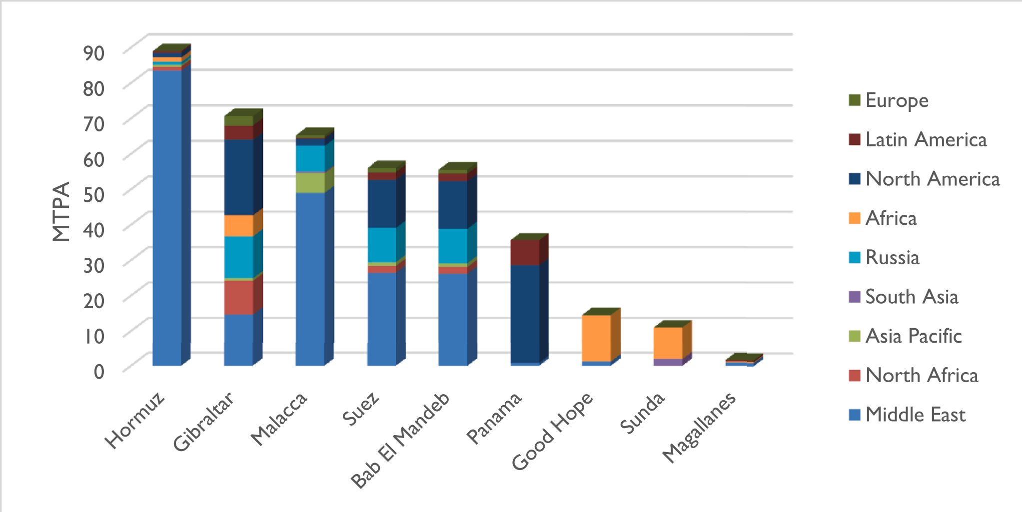

Fig. 11. Base case - LNG exports and their origin region going through every chokepoint.

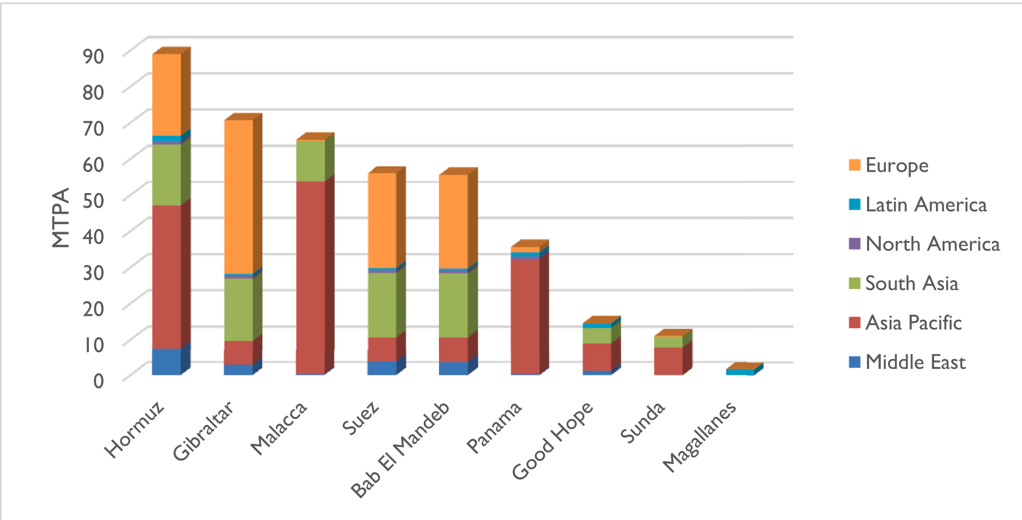

Fig. 12. Base case - LNG imports and their market destinations going through every chokepoint.

5.1. General results

Figs. 9 and 10 results show the LNG trade from the exporters and the importers' side first for the business-as-usual case (no closure of any chokepoint).

In the base case scenario, the LNG trade is around 360+ MTPA for 2021, a bit above the 356.1 MTPA registered for 2020 (International Gas Union, 2021). The leading importers market is the Asian Pacific; Europe is the following market in importance and then South Asia and other markets. From the exporters' side, the AP and the Middle East are the largest exporters regions, with North America and the rest of the world coming next.

Table 10, Figs. 11 and 12 show the LNG traffic per year across the chokepoints. As expected, the Strait of Hormuz is the most transited chokepoint for the LNG tankers because it is the passageway for the LNG exports from Qatar, UAE, and the imports to Kuwait and UAE. Gibraltar Strait is the 2nd most transited choke, possibly because it receives increasing cargo from a chief exporter like the US. From there, we have high traffic in the Malacca Strait, which is the central passage for multiple shipments going to the AP importers, in the labeled "Maritime Silk Road." On the other side of Asia, the BEM strait and the Suez Canal sustain very similar LNG shipments per day. That is consistent with the fact that any LNG cargo entering the Red Sea at one of these points exits by the other. Unlike the oil maritime transit, no loading or unloading ports operate in the Red Sea; so, any LNG cargo entering the Red Sea will have a destination out of that Sea.

On the other side of the world, the Panama Canal presents a relatively minor but potentially growing transit, depending on

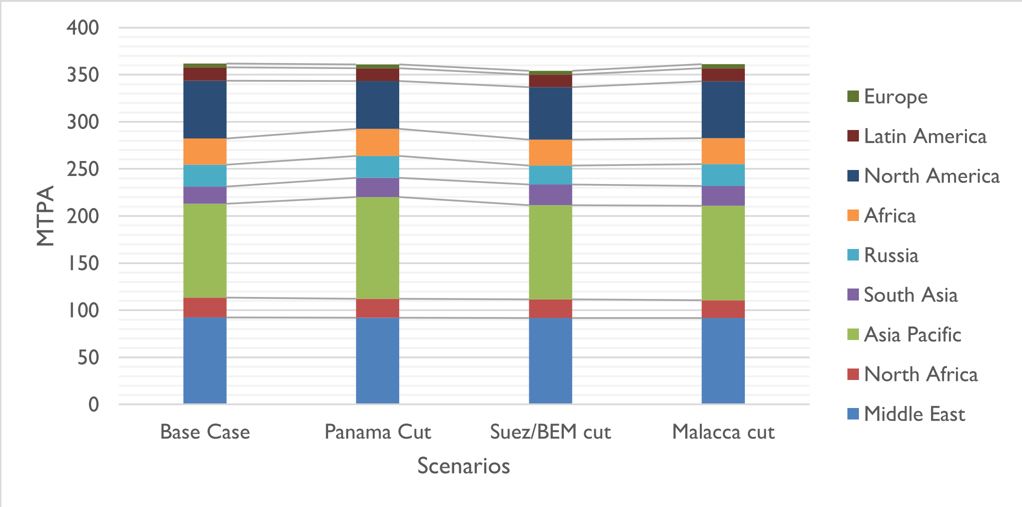

Fig. 13. Exports from every exporting region per scenario.

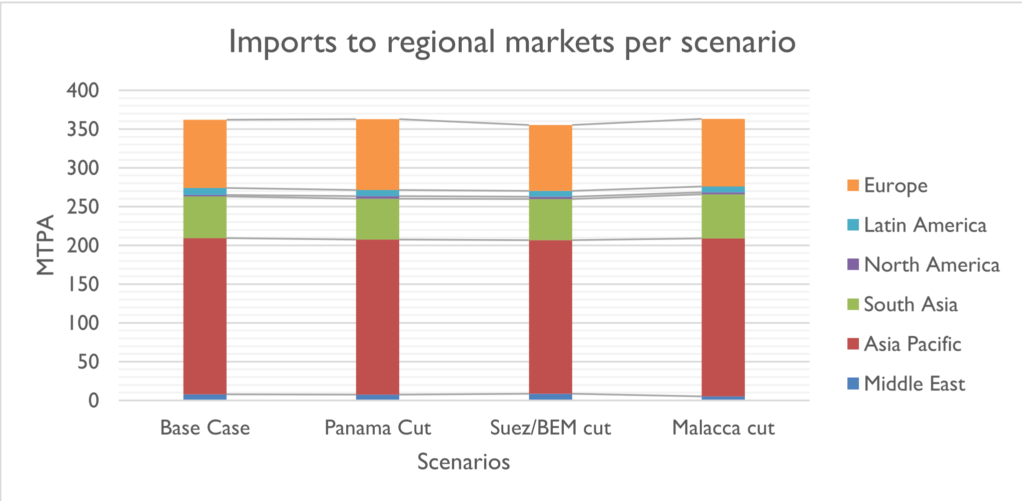

Fig. 14. Imports to every importing market per scenario.

American exports and future projects on Mexico and Canada. The difference is remarkable when comparing all these chokepoints to other possible passages like Cape of Good Horn and Magallanes Strait. As a summary of the results for all the scenarios, Figs. 13 and 14 display the exports and imports per exporting and importing regional markets respectively for every scenario.

The resulting figures for the closure scenarios of Panama Canal, BEM Strait/Suez Canal and the Malacca Strait are in the Appendix. The following subsection discusses the effects of the closures on the trade for each chokepoint.

5.2. Results per disruption scenario

Panama canal

Fig. A-1, A-2 and Table 10 show the LNG trade from the side of exporters, importers, and chokepoints when the model closes the Panama Canal. The long-term disruption of the Panama Canal would have a straight impact on the growing American exports. Connection through Panama Canal to the Pacific Ocean is crucial to make possible the US LNG exports from the Gulf of Mexico, cutting thousands of miles bypassing all South America. With no Panama Canal and only LNG plants in the Gulf of Mexico, the US is farther away from Asia, sending smaller exports to the Asian customers - Fig. 13 and Fig. A-1. The AP exporters (Australia and others) gain from the dwindling American exporters, filling the trade gap and exporting to the Asian markets. There is no large difference for the Middle East (Qatar) since it already produces and sells all its LNG production, unaffected by the Panama Canal disruption.

The Asian and AP markets import slightly smaller LNG quantities - Figs. 14 and A-2, but there is no significant difference since those markets fill the supply gap with the regional Asian exporters and other possible suppliers. On the Western Hemisphere, Europe imports a bit more than in the base case, likely because the US focuses on such a market to replace the losses on Asia.

Watching the panorama from the maritime traffic and routes in Table 10, there are significant changes in the sea transit. The Panama Canal is substituted in unexpected ways. We could expect exporters -Fig. A-3- to travel around South America crossing the Magallanes Strait, but the traffic increases slightly there. Instead, the global LNG traffic focuses more on the route crossing Gibraltar – Suez – BEM - Malacca; without Panama, Gibraltar becomes the most transited chokepoint in the LNG world, above Hormuz, receiving traffic from the US and other exporters. The fewer American exports rather go along the Gibraltar – Suez – BEM – Malacca loop to reach the AP importers - Fig. A-4, making Malacca Strait the 2nd most transited chokepoint. Suez Canal and BEM would also become more vital with increasing shipments going through them.

As to the global LNG trade, the quantities are similar to the Base Case, showing how the market might adapt to replace the Panama Canal and the partial absence of the US.

Bab el-Mandeb (BEM) strait and the Suez Canal

These two chokepoints are intrinsically linked since they are endpoints of the Red Sea; any total blockade of one would render the other useless for any maritime traffic with a destination beyond the Red Sea. Since there are no liquefaction nor regasification plants at the Red Sea, the impact of closing the Suez Canal or BEM is the same. Compared with the base case, the most affected exporters would be South Asia, Russia, Europe (Norway), North America (the US), and North Africa - Figs. 13 and A-5 -with some minor effects on the Middle East. Their decrease in exports is understandable since these exporters use BEM/Suez as passageways to their importing markets. Even though the Middle East is near the Red Sea, Qatar is still competitive to allocate LNG exports in Europe by circumnavigating Africa because the LNG production costs are significantly smaller than other exporters. And even when the shipping costs increase, Qatar could still play with the net profits and be attractive to the European importers.

On the importing side - Figs. 14 and A-6, the European and Asian markets would be the most affected, pointing out how crucial these two chokepoints are for connecting these two continents. Europe would have difficulties getting supplies from the Asian exporters, using African supplies and others to fill the gap.

From the side of the maritime routes, there are noteworthy changes. With no Suez/BEM, one important sea loop from Gibraltar to Malacca Strait is broken, and the LNG suppliers have no choice but to resort to the Cape of Good Hope. From Figs. A-7 and A-8, the South African route registers 4+ times the traffic than in the base case, unlike the Magallanes Strait when the Panama Canal is cut. Also, the traffic through the Malacca Strait decreases a bit because fewer supplies are coming from the Western hemisphere; however, there is an increase going through the alternative route, the Sunda Strait. More supplies come from Africa to the AP basin; consequently, the Sunda Strait is the shortest route. Gibraltar decreases its LNG transit significantly because it is part of the Suez / BEM route.

Finally, and in general, the total closure of the Red Sea decreases in some MTPA the total LNG trade, reflecting how vital these chokepoints are for the energy markets connection between Western and Eastern hemispheres.

Malacca strait

From all the closure scenarios, this is the less impactful, probably because Malacca Strait counts with some nearby alternatives to the maritime flow. In the Java Sea, the maritime network could find replacements at the Sunda and the Lombok Straits. It would be necessary to close these three straits plus the Javan and Indonesian seas to get the region impassable and require long circumnavigational routes. The exporting - Figs. 13 and A-9- and importing quantities - Figs. 14 and A-10- by region are similar to the original case scenario, except for North Africa, Africa, and South Asian exporters, which show minor decreases. This assessment is coherent with the chokepoints and LNG routes traffic, Figs. A-11 and A-12. There are no considerable changes when comparing the LNG flowing through the chokepoints with the base case, except that the Sunda Strait becomes the 2nd most transited chokepoint with more LNG traffic than the Malacca Strait in the original base scenario.

That would not mean that the closure of the Malacca Strait would not affect the LNG market. It would increase the shipping times and costs, and the closest alternative, the Sunda Strait, is still difficult to navigate. It is just that the alternative distances are not nearly as long as circumnavigating Africa or South America in the other disruptions.

6. Discussion

The implications from the previous scenarios results are various. Closing the Panama Canal would have a straight impact on the North American LNG exporters with plants located on the Atlantic Coast, i.e. all the US producing LNG plants. Thinking that there are many US LNG projects located in the Gulf of Mexico and multiple others from Canada and Mexico located on the Atlantic basin (Corbeau and Ledesma, 2016), the continuous operation of the Panama Canal for the LNG market is crucial for the North American exporters and the Asian Pacific importers in search of diversification.

The disruption of the Suez Canal or the BEM Strait would be a more significant blow to the LNG market (indeed to any market) because it involves a key LNG route connecting Europe, Africa and Asia, i.e. the major importing and exporting LNG markets. In the simulations, the exporters become less efficient in exporting and reaching markets, decreasing in some MTPA the global trade. Thus, the smooth maritime operation and management of the Suez Canal or BEM Strait is crucial for all the LNG players. In case of the Malacca Strait, the consequences would be delays and increasing operational costs, but there are relatively closer alternatives of straits and passageways to bypass Malacca and connect AP markets to exporters on the West, turning it less serious than the previous cases. However, in case of a major conflict or disturbance, closing the Indonesian seas or the South China sea, the impact would potentially

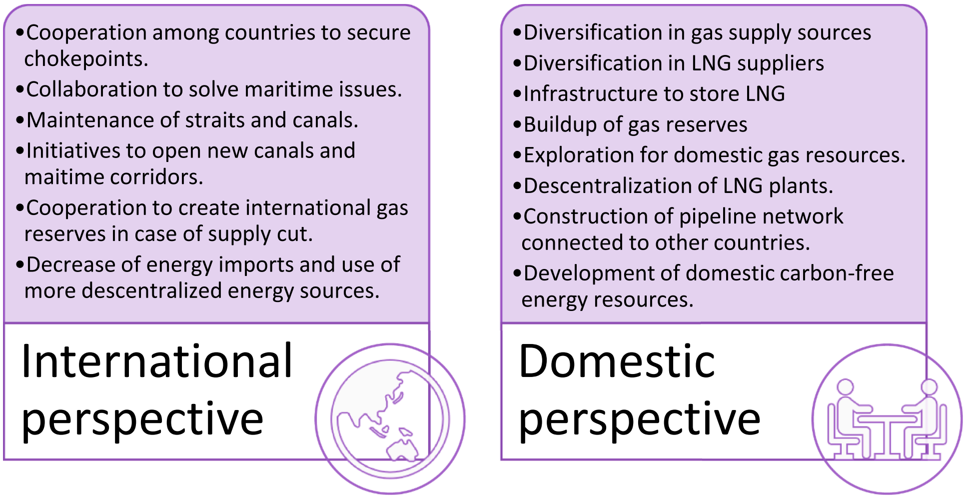

Fig. 15. Policy measures for preventing and mitigating chokepoint closures in the LNG market.

increase in the interruption of LNG supply operations for AP basin.

From this analysis, the transport policy implications are multiple and from different standpoints, as in Fig. 15. We can consider an international perspective to secure maritime routes and the smooth flow of energy commodities across the chokepoints. Global cooperation among seafaring and neighboring countries to chokepoints should be shaped effectively to increase maritime security. That aspect means decreasing the threats of piracy, terrorism, attacks, and conflicts, patrolling the critical routes and chokepoints, and maintaining the infrastructure of artificial canals and the natural passage of narrow spots at the straits. That cooperation could also encompass how to supply gas from alternative gas reserves in case of disruptions occur anytime.

From a domestic policy, importers should work on energy supply, energy security, and energy diversification topics. They should maintain the LNG and pipeline gas supply robust, not depending on just one supplier but many, maximizing the security of the route used for any supply. They should consider avoiding bottlenecks and chokepoints as much as possible and working to increase the flow security across such spots. Energy supply and security also refer to how the countries should promote an energy policy towards developing indigenous gas resources, decreasing the dependence on critical imports. Many of the gas importing countries lack indigenous gas resources; however, we can consider the experience of the US to unlock shale gas successfully to turn from large gas importer to prominent exporter in a matter of some decades. Countries like China and Argentina are working to repeat that experience. Other countries could follow suit to unlock and produce their domestic gas resources, decreasing the dependence on maritime or pipe imports and the strain on vital maritime routes and chokepoints (Vivoda, 2010). From the diversification side, countries should also work with a long-term view to diversify the energy resources portfolio and decrease the reliance on gas and fossil fuels, increasing the consumption of carbon-free resources, which are more universal and environmentally friendly. That would also reduce imports from remote regions.

Further, we can watch this topic in a case-by-case scenario for the chokepoints and the exporters and importers. As to the Panama Canal, the relevant infrastructure should be maintained in a good condition and expanded to make it available for any tanker, since we could expect that the gas and energy flow would increase in the future. Also, governments could promote alternatives to the Panama Canal, like the Nicaragua canal in Central America, a larger project (in length and size) than the Panama canal (Miah et al., 2019; Yip and Wong, 2015). If materialized, that Canal would decrease the criticality of the Panama Canal route for the North American LNG exports. However, the project funding is facing issues from the Chinese owners of the project. There are growing concerns about the project's environmental impact, especially in Lake Nicaragua, which would shorten the Canal length (Muller, 2019).

In the case of the Suez Canal and BEM Strait, the most readily and immediate option is circumnavigating Africa (Notteboom, 2012), which increases costs for any exporter and difficult the supplies for any European importer and partially to the Asian importers. As with the Panama Canal, the owners and stakeholders should maintain adequately the Suez Canal, with plans to enlarge its dimensions to provide a route for large tankers and avoid operational incidents like the Ever Given or any other regarding extreme weather.

One alternative to the Suez Canal blockage is the construction of another canal, running in parallel near the Egyptian border, that would take the ships' traffic to Israel. This is the "Route of the Exodus", running along the Gulf of Aqaba and Straits of Tiran (Miah et al., 2019) in places near Jordan, Saudi Arabia, and Israel; however, that location is susceptible to conflicts. Further, that project would involve connecting the Eilat port of Israel on the Eastern side of Sinai to the Mediterranean coast of Israel, in a very long canal, probably 250 km long. Not only is Suez Canal shorter by 100 km, but also the topographic features in Eastern Sinai are widely different, making the digging process complicated and costly (Abay, 2021). The project received some support from Israel and UAE, but it is unclear when or whether it would proceed (Abay, 2021).

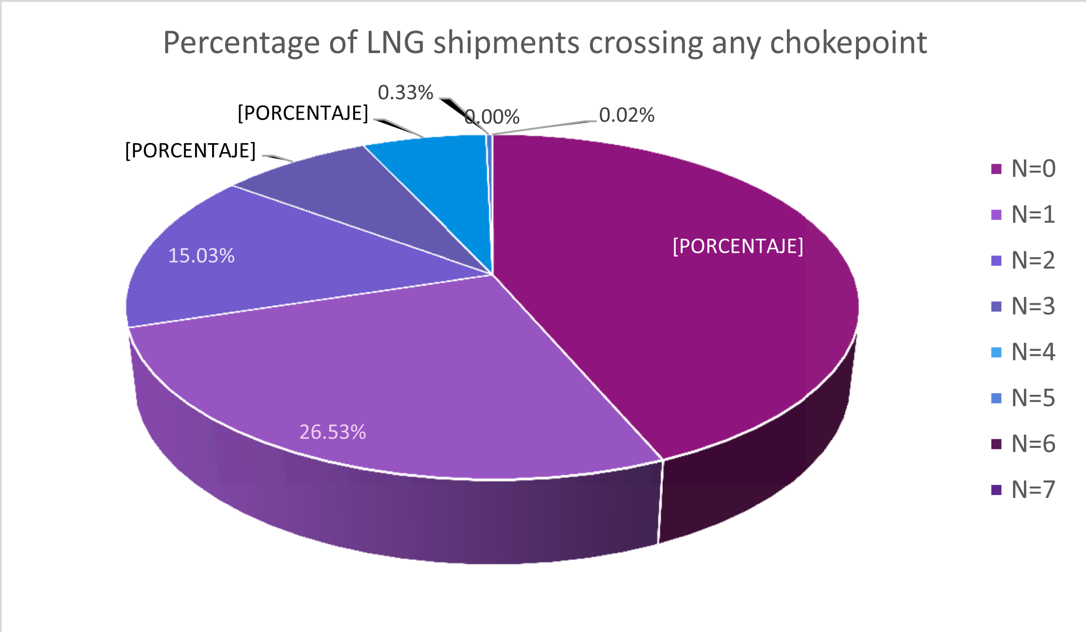

Fig. 16. Percentage of LNG shipments going through N chokepoints in a year with present time data (2021).

There are no near alternatives to bypassing the BEM Strait, so keeping it clear from disruptions depends on international cooperation and maritime patrolling, especially when we think of piracy. In a broader and longer-term vision, pipelaying gas lines connecting the Middle East and the Persian Gulf gas fields to Turkey and from them to Europe is an old cherished initiative, with political difficulties due to the Middle East disputes, wars, and attacks in different countries.

The Malacca Strait's maintenance is a matter of international cooperation because it borders several countries with disputes about who should care for its cleaning and traffic regulation. However, they also benefit from the maritime commerce, as worldwide ports are located nearby because of the strategic location of the strait

In the case of countries, exporters like the US should decentralize their LNG production centers. The Gulf of Mexico is the American LNG productive area, but it depends on the Panama Canal to connect to Asia. Counting with LNG plants in the Western Coast could alleviate such dependence and avoid that chokepoint. Similarly, for the future Mexican and Canadian LNG projects expected in this decade (International Gas Union, 2021), counting with LNG productive plants in the Atlantic and Pacific Coasts could guarantee strategic access to different regional markets.

For the importing countries, supply security is a concern in case any disruption takes place. One of the first measures they may take is increasing and maintaining LNG reserve infrastructure to supply their internal markets if the LNG supply chain is cut. Also, some countries reinject gas in underground formations, where it could be safely stored until consumed. Importers may look for such rock formations to store gas once it is re-gasified and create strategic reserves in their territories.

In a more specific case, we have China, the expected largest energy and gas consumer in some years. China should seek to materialize different pipeline projects to connect to large gas producers located in Central Asia, South East Asia, and Russia, probably one of the world's largest gas networks. With time, such a network may extend to the Middle East, crystalizing the Silk Road projects (Lin, 2019). On the maritime side, the influence to secure routes or support projects opening new canals like Nicaragua Canal may help secure supply. Also, the opening of the Arctic Sea due to global warming (Schach and Madlener, 2018; Schøyen and Bråthen, 2011) could clear a new shorter sea lane for the LNG trade, Russian LNG exports, and potential North American producers (Liu and Kronbak, 2010).

However, reconsidering the intensification of the chokepoints transit in future years, we could have a reversal of fortunes. NG is expected to bridge the energy world towards renewable energies. Europe is preparing for the transition soon (among other reasons, to stop the dependence on Russian gas imports), and as we have more carbon-emission restrictions, we could expect other nations to follow suit. In a future world with carbon-free energy sources commercially developed, the use of fossil fuels would have decreased considerably, shifting the energy resources map, the energy trade, and finally, the energy imports and energy dependence. Renewable energies are universal and varied in their geographical distribution, avoiding their concentration in some regions of the world, away from the main markets. With the possibility that every country develops its renewables portfolio, the gas imports could finally decrease significantly after playing their energy bridge role. In turn, that would alter the geopolitical map of energy, the balance of power between importers/exporters, and finally, decrease the transit and dependency on chokepoints, at least on the energy world terms.

When would that happen? It is difficult to say, but it would take time. Energy transitions do not happen overnight, but they redraw the resources map, energy trade, political power, and influence among the players when they do. This future scenario is something to consider in the long term when thinking of the future role of chokepoints.

7. Conclusions

Chokepoints are the Achilles heels of the sea trade routes. These passageways are very narrow and sensitive to blockade and closure for reasons such as operational incidents, war, conflicts among neighboring countries, piracy, or others. They play a fundamental role in the energy world because oil and natural gas "flow" along them. The geographical distribution of producers and consumers, separated by oceans and continents, turns sea trade fundamental. NG is considered the future fossil fuel, with projections to increase demand, so secure chokepoints are critical for the LNG value chain system.

Fig. 16 stresses the importance of chokepoints by listing how many LNG shipments cross any given number of the chokepoints listed in Table 6, as obtained from the simulations in the base case scenario for the year 2021. More than half of the shipments go across any chokepoint and critical passageway, with many crossing two or more chokepoints, telling about how serious these passages are for gas flow now.

This paper proposes to fill the literature gap about the effects of chokepoints disruptions in the LNG trade. The study uses a model to simulate the LNG trade, using Agent-Based Modeling (ABM). There are several chokepoints to be considered for study; this work simulates the closure of three of them: a) Panama Canal, b) Bab el-Mandeb and Suez Canal, c) Malacca Strait because of their potential repercussions on the energy trade and their alternatives and energy policy implications. The ABM LNG model is tested and validated against the LNG exports for Qatar and the US (two of the largest LNG exporters) for 2016 and 2018. Then the model is compared in the LNG transit through chokepoints with simulated vs. real data. The model demonstrates accuracy for reflecting past LNG trade and traffic in both cases.

Responding to the proposed questions on Section 1, the LNG trade is not greatly disturbed by the closure of any of these chokepoints, except in the case of the Suez Canal because it affects a major maritime route and the alternative is a long circumnavigation around Africa. The immediate options to bypass any of these closures are to use alternative routes, some that could be long like in the case of Panama and Suez Canals, and some shorter like the Malacca Strait. Thanks to these alternatives and the large number of LNG exporters, the market could find ways to replace exporters that connected to different regional markets by crossing the closed chokepoints. However, in case there are no alternative maritime routes (as with the Strait of Hormuz), the situation is more complex.

Other long-term options are promoting the construction of alternative canals to these chokepoints, patrolling the routes to avoid piracy and promote security, building alliances from different countries to keep conflicts away from them and building gas networks to bypass any closure. Some very long-term options involve energy transitions to phase out fossil fuels consumption by using domestic renewable energy portfolios, both more environmentally friendly, adaptable and sustainable.

Future work in this subject may take a variety of directions. First, we may consider the future effects of chokepoints disruptions, modeled in a more intensive and future market with more congested sea lanes and a more weather-instable world. Then, simulating the disruption of critical chokepoints like the Strait of Hormuz is interesting because of its complicated nature. Also, we may think about how critical the simultaneous disruption of two or more chokepoints and their effect on the energy trade could be. Taking another direction, we could complement the work performed by other authors in the oil trade by using ABM as a new potential methodology. Beyond the energy world, the applications are multiple when we think of the global food network or other vital industries for our economy and society.

Author statement

All the authors contributed to the realization of this paper. Abel Meza: conceptualization, methodology, formal analysis, investigation, and writing original draft preparation. Ibrahim Ari: formal analysis, writing review – editing, and supervision. Mohammed Saleh Al-Sada: formal analysis, writing review – editing, and supervision. Muammer Koc: formal analysis, resources, writing review – editing, and supervision.

Funding

The funding for this work was supported by the Qatar Foundation through Hamad Bin Khalifa University. Open Access funding provided by the Qatar National Library.

Declaration of Competing Interest

None.

Appendix A. Parameters of Agents

Table A-1
Exporters and parameters.

Exporter	Location	Region	Initial Reserves (BCM)	Liquefaction Capacity (MTPA)
Qatar	Ras Laffan, Qatar	Middle East	24,700	77.1
USA	Sabine Pass, Porth Arthur, USA	North America	12,900	46.6
Russia01	Sabetta, Russia	Russia	19,000	17.16
Australia	City of Darwin, Australia	Asia Pacific	2400	87.6
Papua	Port Moresby, Papua	Asia Pacific	200	6.9
UAE	Abu Dhabi 4644, UAE	Middle East	5900	5.8
Indonesia	Bontang, Kalimantan Indonesia	South Asia	1400	26.5
Malaysia	Bintulu, Sarawak, 97,000, Malaysia	Asia Pacific	900	30.5
Brunei	Kampong Lumut, Mukim Liang, Belait, Brunei	Asia Pacific	200	7.2
Cameroon	Kribi, Cameroon	Africa	135.1	2.4
Angola	Soyo, Angola	Africa	311.5	5.2
Equatorial Guinea	Bioko, Bioko Sur, Región Insular, 240, Guinea Ecuatorial	Africa	36.8	3.7
Nigeria	Bonny Island, Bonny, Rivers, Nigeria	Africa	5400	22.2
Oman	Qalhat, Oman	Middle East	700	10.4
Algeria	Arzew, Algeria	North Africa	4300	25.5
Lybia	Marsa El Brega, Al Wahat, Lybia	North Africa	1400	3.2
Egypt	Damietta, Egypt	North Africa	2100	2.2
Trinidad & Tobago	Point Fortin, Trinidad and Tobago	Latin America	300	14.8
Norway	Melkøya Island, Hammerfest, Norway	Europe	1500	4.2
Peru	Cañete, Lima, Perú	Latin America	300	4.5
Russia02	Sakhalin 2, Russia	Russia	19,000	9.6
Argentina	Partido de Bahía Blanca, Buenos Aires, Argentina	Latin America	400	0.5

Table A-2
Importers and parameters.

Importer	Location	Region	Demand (MTPA)	Regasification Capacity (MTPA)
United Kingdom	Milford Haven, Pembrokeshire, United Kingdom	Europe	13.43	38.1
France	Fos-Sur-Mer, Istres, France	Europe	13.06	25
Spain	Port of Bilbao, Zierbena, Biscay, Spain	Europe	15.37	43.8
India	Ennore Port, Tamil Nadu, India	South Asia	26.63	33.3
China	Diefu, Shenzhen, China	Asia Pacific	68.91	77.4
Japan	Semboku, Japan	Asia Pacific	74.43	210.5
South Korea	Incheon, South Korea	Asia Pacific	40.81	125.8
Taiwan	Taichung Port, Taiwan	Asia Pacific	17.76	14
Belgium	Zeebrugge, Lissewege, Brugge, West-Vlaanderen	Europe	3.21	6.6
Bangladesh	Moheshkhali Jetty, Dhighi Road, Bangladesh	South Asia	4.18	7.6
Brazil	Pecém, São Gonçalo do Amarante, Fortaleza, Ceará, Brasil	Latin America	2.39	11.6
Argentina	Belén de Escobar, Partido de Escobar, Buenos Aires, Argentina	Latin America	1.37	3.4
Canada	Saint John, New Brunswick, Canada	North America	0.63	7.5
Chile	Mejillones, Provincia de Antofagasta, Chile	Latin America	2.69	5.5
Colombia	Cartagena de Indias, Dique, Bolívar, Caribe, Colombia	Latin America	0.3	4.5
Croatia	Krk, Primorsko-goranska županija, Hrvatska	Europe	0	2.3
Greece	Athens, Greece	Europe	2.2	4.6
Israel	Sharon, Haifa, Israel	Middle East	0.57	3.9
Italy	Livorno, Toscana, Italia	Europe	9.07	11
Kuwait	Mina Al-Ahmadi, Kuwait	Middle East	4.07	5.7
Lithuany	Klaipėda Seaport, Lithuany	Europe	1.44	2.4
Mexico	Manzanillo, Colima, México	North America	1.88	16.8
Netherlands	Maasvlakte Rotterdam	Europe	5.33	9
Pakistan	Port Qasim Staff Colony	South Asia	7.42	9.5
Poland	Świnoujście seaport	Europe	2.7	4.1
Portugal	Terminal de GNL- Transgás Atlântico, Sines, Setúbal, Alentejo Litoral, Alentejo	Europe	4.07	5.8
Singapore	Jurong Island, Southwest, Singapore	South Asia	3.19	11
Thailand	Rayong, Thailand	South Asia	5.61	11.4
Turkey	Marmaraereğlisi, Turkey	Europe	10.72	18.1
UAE	Jebel Ali	Middle East	1.46	6

Appendix B. Panama Canal disruption

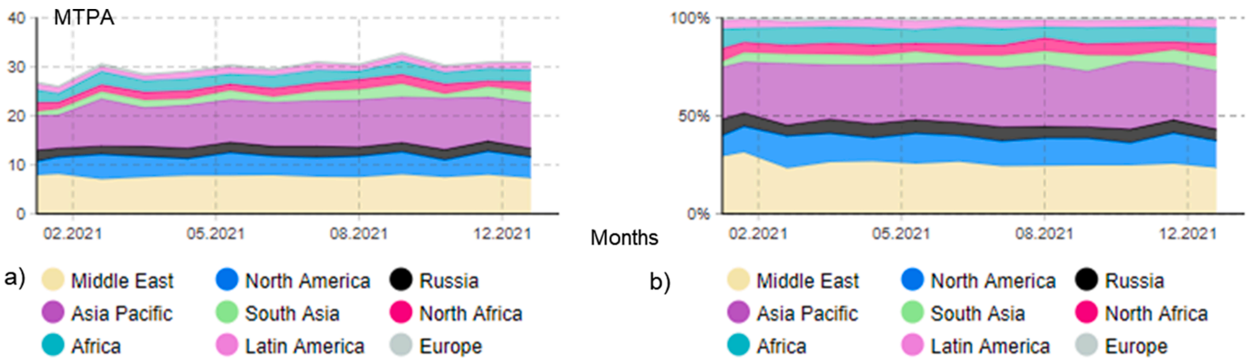

Fig. A-1. No Panama Canal - LNG Exports origin regions a) per month in MTPA b) shares per month.

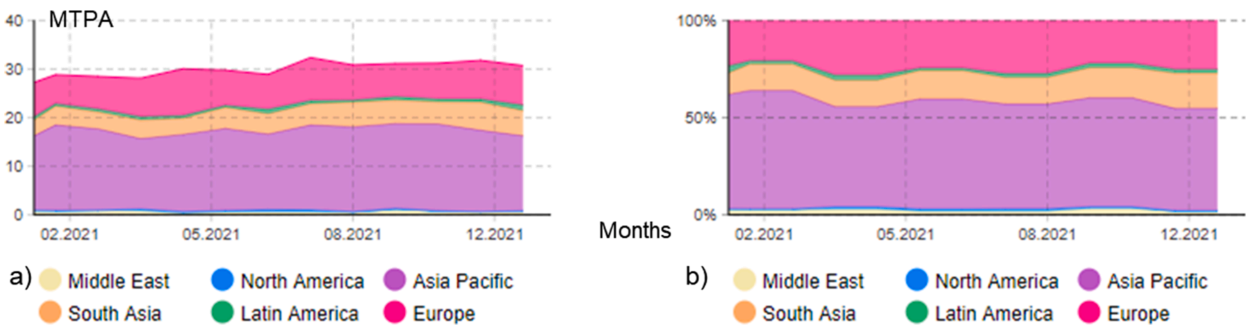

Fig. A-2. No Panama Canal - LNG Imports destination regions a) per month in MTPA b) shares per month.

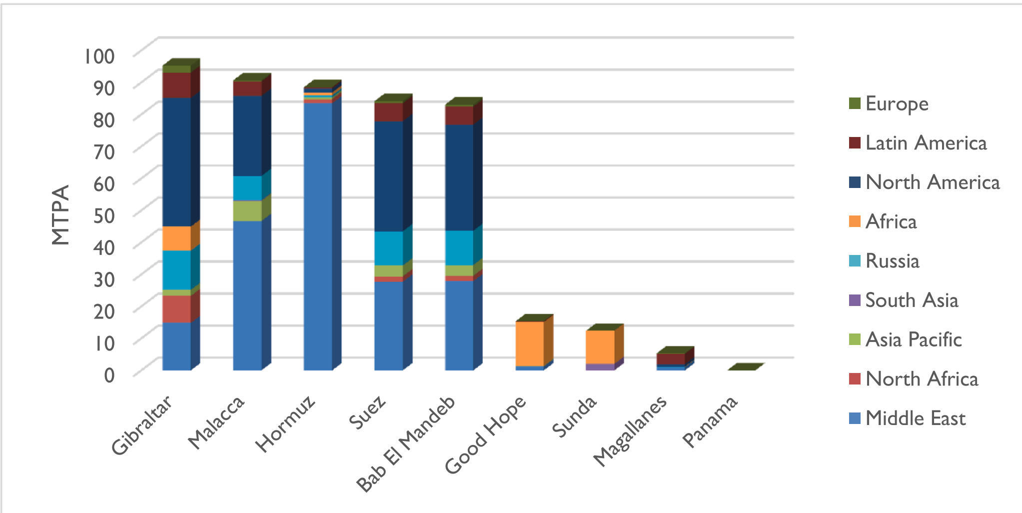

Fig. A-3. No Panama Canal - LNG exports and their origin region going through every chokepoint.

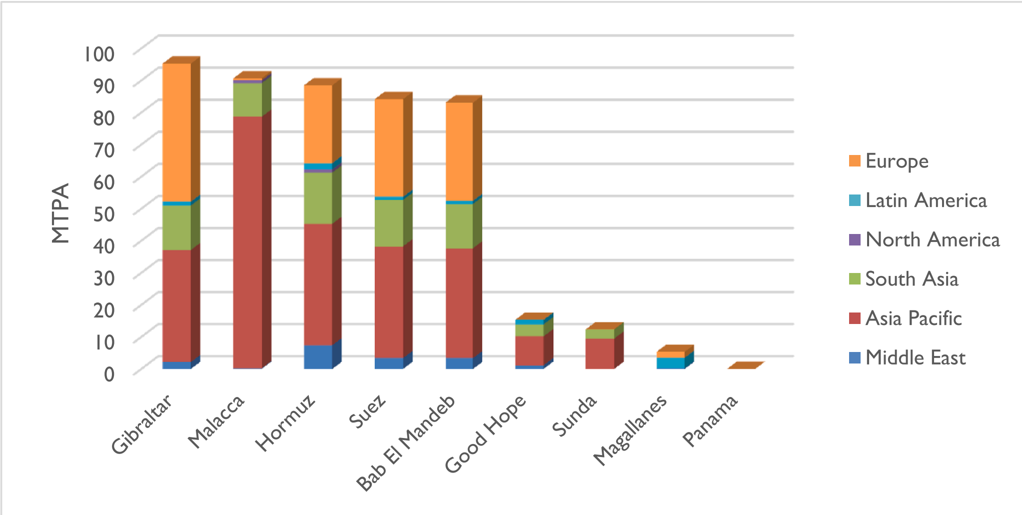

Fig. A-4. No Panama Canal - LNG imports and their market destinations going through every chokepoint.

Appendix C. Suez Canal / BEM disruption

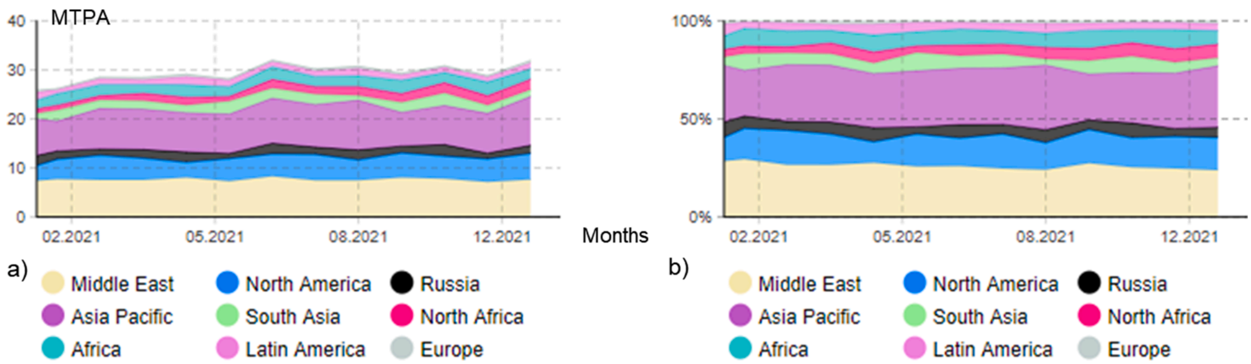

Fig. A-5. No Suez Canal / BEM - LNG Exports origin regions a) per month in MTPA b) shares per month.

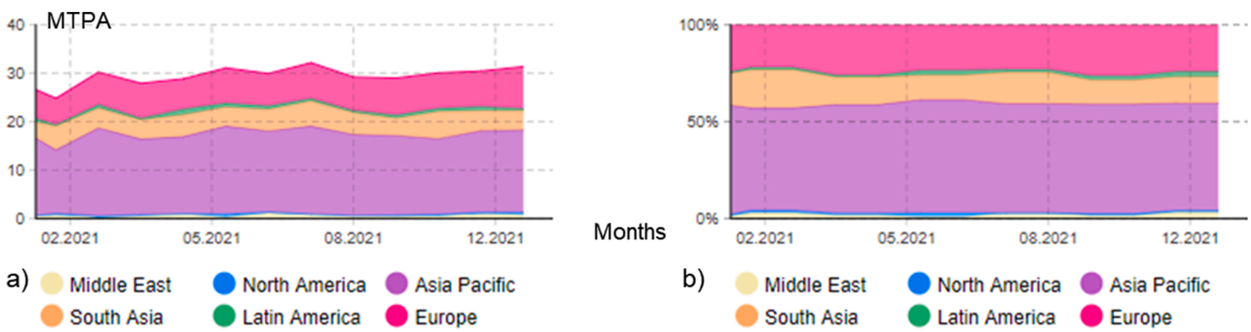

Fig. A-6. No Suez Canal / BEM - LNG Imports destination regions a) per month in MTPA b) shares per month.

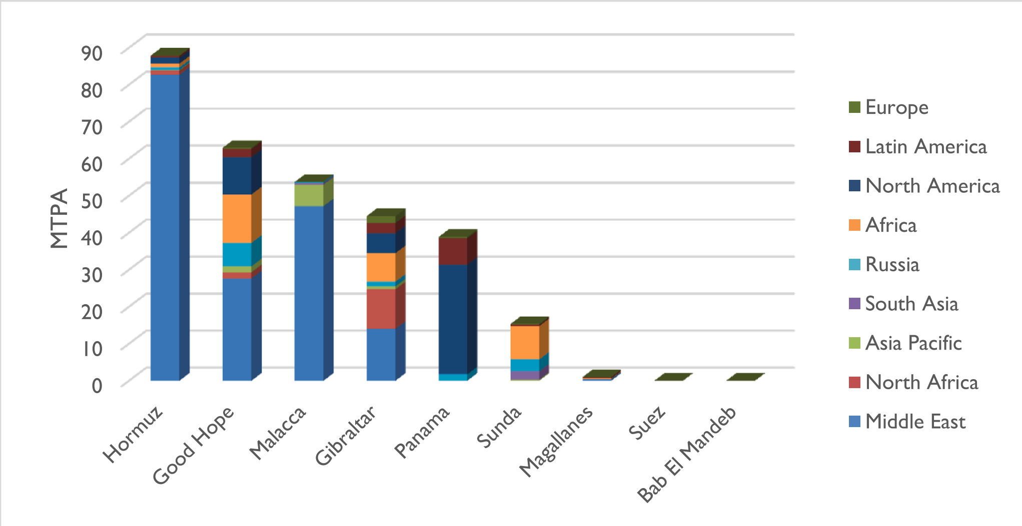

Fig. A-7. No Suez Canal / BEM - LNG exports and their origin region going through every chokepoint.

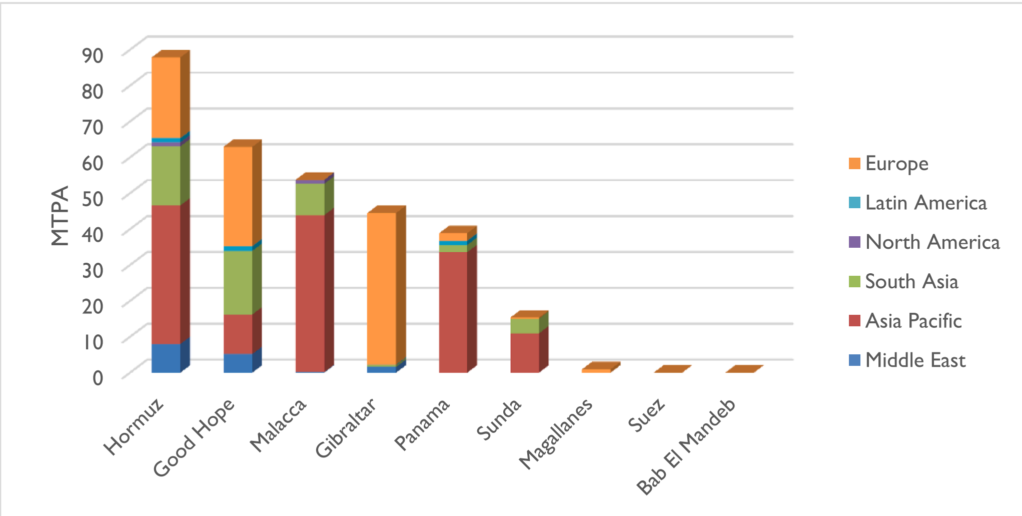

Fig. A-8. No Suez Canal / BEM - LNG imports and their market destinations going through every chokepoint.

Appendix D. Malacca Strait disruption

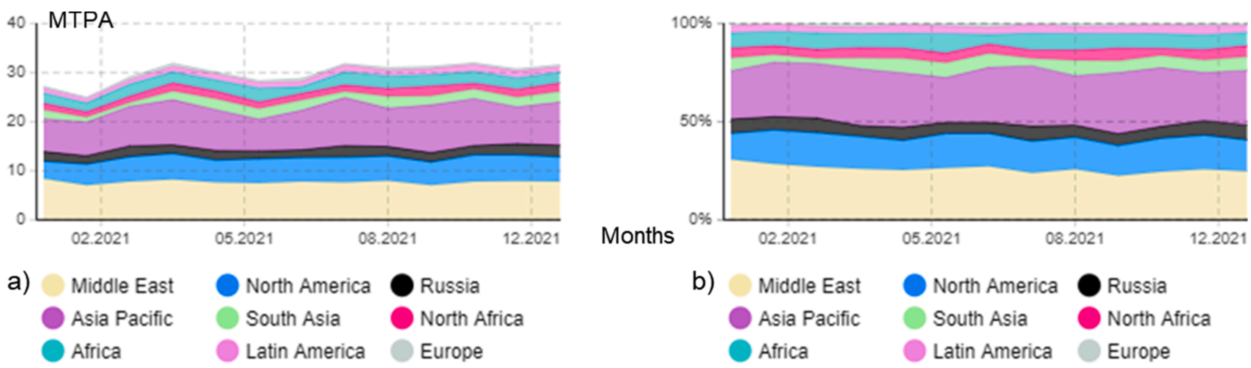

Fig. A-9. No Malacca Strait - LNG Exports origin regions a) per month in MTPA b) shares per month.

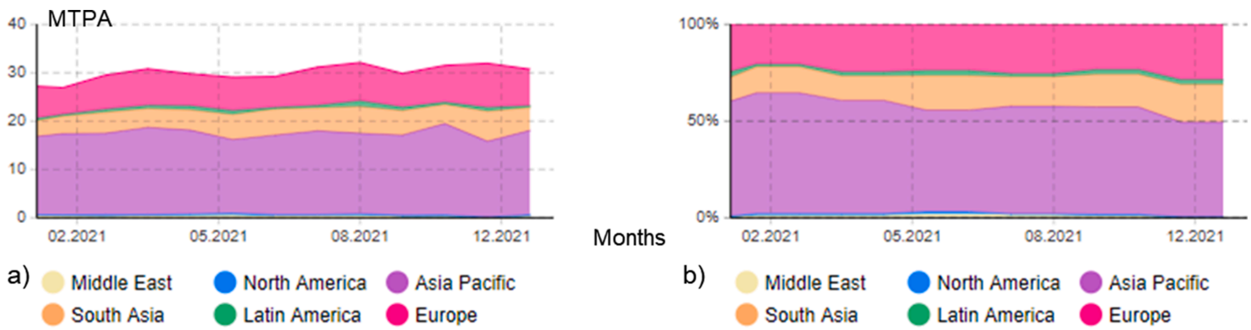

Fig. A-10. No Malacca Strait - LNG Imports destination regions a) per month in MTPA b) shares per month.

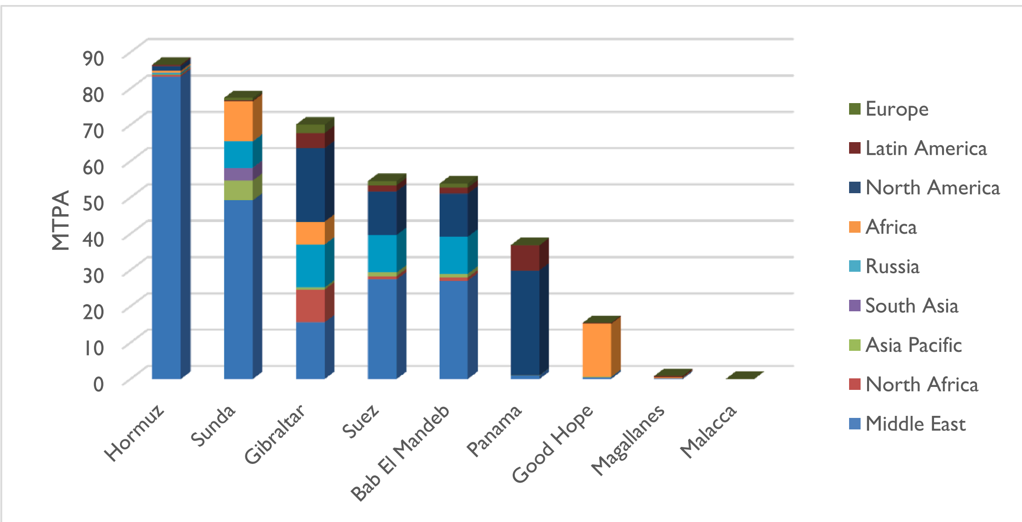

Fig. A-11. No Malacca Strait - LNG exports and their origin region going through every chokepoint.

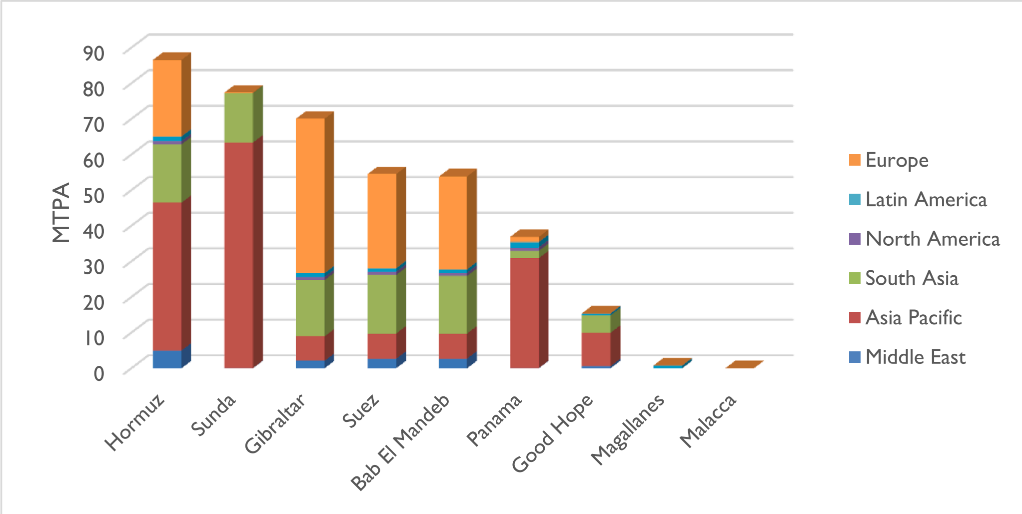

Fig. A-12. No Malacca Strait - LNG imports and their market destinations going through every chokepoint.

References

Abar, S., Theodoropoulos, G.K., Lemarinier, P., O'Hare, G.M.P., 2017. Agent based modelling and simulation tools: a review of the state-of-art software. Comput. Sci. Rev. 24, 13–33. https://doi.org/10.1016/j.cosrev.2017.03.001.

Abay, E.G., 2021. Russia seeks to create alternative to Suez Canal via Northern Sea Route.

Alderson, D.L., Funk, D., Gera, R., 2020. Analysis of the global maritime transportation system as a layered network. J. Transp. Secur. 13, 291–325. https://doi.org/10.1007/s12198-019-00204-z.

AnyLogic Company, 2021. AnyLogic Software [WWW Document]. URL https://www.anylogic.com/(accessed 10.1.21).

Ari, I., Koc, M., 2021. Philanthropic-crowdfunding-partnership: a proof-of-concept study for sustainable financing in low-carbon energy transitions. Energy 222, 119925. https://doi.org/10.1016/j.energy.2021.119925.

Ari, I., Koc, M., 2019. Sustainable financing for sustainable development: agent-based modeling of alternative financing models for clean energy investments. Sustainability 11, 1967. https://doi.org/10.3390/su11071967.

Bailey, R., Wellesley, L., 2017. Chatham House Report Chokepoints and Vulnerabilities in Global Food Trade. London, UK.

BBC, 2021a. Suez Canal: ships stuck in "traffic jam" as salvage efforts continue [WWW Document]. URL https://www.bbc.com/news/world-middle-east-56538653 (accessed 11.21.21).

BBC, 2021b. Suez Canal reopens after giant stranded ship is freed.

Bendall, H.B., 2010. Cost of piracy: a comparative voyage approach. Marit. Econ. Logist. 12, 178–195. https://doi.org/10.1057/mel.2010.1.

Birol, F., Corben, J., Priddle, R., 2011. Are we Entering a Golden Age of Gas? - World Energy Outlook 2011. Paris, France.

BP, 2020. BP Statistical Review of World Energy 2020. London, UK.

Brigham, L., 2021. The Suez Canal and Global Trade Routes. In: Proc. US Nav. Inst, p. 147.

Corbeau, A.-.S., Ledesma, D., 2016. LNG Markets in Transition: The Great Reconfiguration. Oxford University Press, Oxford, UK.

Dimitroff, T.J., 2014. Cross-border oil and gas pipeline risk and sustainable mitigations. J. World Energy Law Bus. 7, 287–339. https://doi.org/10.1093/jwelb/jwu024.

Energy Information Agency, 2017. World Oil Transit Chokepoints [WWW Document]. EIA - Indep. Stat. Anal. URL https://www.eia.gov/international/analysis/special-topics/World_Oil_Transit_Chokepoints (accessed 11.18.21).

Feng, S., 2018. System dynamics model for battery recycling of electric vehicles in Anylogic simulation. Int. J. Internet Manuf. Serv. 5, 405. https://doi.org/10.1504/IJIMS.2018.095260.

Feyrer, J., 2021. Distance, trade, and income — The 1967 to 1975 closing of the Suez canal as a natural experiment. J. Dev. Econ. 153, 102708 https://doi.org/10.1016/j.jdeveco.2021.102708.

Foss, M.M., 2012. Introduction to LNG. An overview on Liquefied Natural Gas (LNG), Its properties, the LNG Industry,And Safety Considerations. Austin, Texas.

Fu, X., Ng, A.K.Y., Lau, Y.Y., 2010. The impacts of maritime piracy on global economic development: the case of Somalia. Marit. Policy Manag. 37, 677–697. https://doi.org/10.1080/03088839.2010.524736.

Fulwood, M., Sharples, J., Henderson, J., 2022. Ukraine Invasion: What This Means for the European Gas Market - Oxford Institute for Energy Studies. Oxford Institute.

Funk, D., 2017. Analysis of the Global Maritime Transportation System and its Resilience. Naval Postgraduate School.

Gong, X., Lu, J., 2018. Strait/canal security assessment of the Maritime Silk Road. Int. J. Shipp. Transp. Logist. 10, 281–298. https://doi.org/10.1504/IJSTL.2018.091674.

Graham, E., 2015. Maritime security and threats to energy transportation in Southeast Asia. RUSI J 160, 20–31. https://doi.org/10.1080/03071847.2015.1031522.

Heidari, S., Weber, C., 2017. The changing landscape of world gas markets at the horizon 2020. In: 2017 14th International Conference on the European Energy Market (EEM). IEEE, pp. 1–6. https://doi.org/10.1109/EEM.2017.7981888.

Heppenstall, A.J.J., Crooks, A.T., See, L.M., Batty, M., 2012. Agent-Based Models of Geographical Systems, Agent-Based Models of Geographical Systems. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-90-481-8927-4.

IEA, 2012. Golden Rules for a Golden Age of Gas.

International Gas Union, 2021. 2021 World LNG Report. IGU, Barcelona, Spain.

International Gas Union, 2020. 2020 World LNG Report. IGU, Barcelona, Spain.

International Gas Union, 2019. 2019 World LNG Report. IGU, Barcelona, Spain.

International Gas Union, 2018. 2018 World LNG report. IGU, Barcelona, Spain.

International Gas Union, 2017. 2017 World LNG Report. IGU, Barcelona, Spain.

Kilisek, R., 2014. Economics of Alaskan and US gulf coast LNG projects. Break. Energy.

Kimura, S., Morikawa, T., Singh, S., 2015. Sea lane security of oil and liquefied natural gas in the East Asia Summit Region.

Kitamura, T., Managi, S., 2017. Energy security and potential supply disruption: a case study in Japan. Energy Policy 110, 90–104. https://doi.org/10.1016/j.enpol.2017.08.008.

Komiss, W., Huntzinger, L., 2011. The Economic Implications of Disruptions to Maritime Oil Chokepoints. Cna.

Kosai, S., Unesaki, H., 2016. Conceptualizing maritime security for energy transportation security. J. Transp. Secur. 9, 175–190. https://doi.org/10.1007/s12198-016-0173-2.

Ledesma, D., Henderson, J., Palmer, N., 2014. The Future of Australian LNG Exports: Will Domestic Challenges Limit the Development of Future LNG Export Capacity? Oxford Institute for Energy Studies, Oxford, UK.

Lee, J.M., Wong, E.Y., 2021. Suez Canal blockage: an analysis of legal impact, risks and liabilities to the global supply chain. In: MATEC Web Conf. 339, 01019. https://doi.org/10.1051/matecconf/202133901019.

Leung, G.C.K., 2011. China's energy security: perception and reality. Energy Policy 39, 1330–1337. https://doi.org/10.1016/j.enpol.2010.12.005.

Lin, W., 2019. Transport geography and geopolitics: visions, rules and militarism in China's Belt and Road Initiative and beyond. J. Transp. Geogr. 81, 0–1. https://doi.org/10.1016/j.jtrangeo.2019.05.001.

Liu, M., Kronbak, J., 2010. The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. J. Transp. Geogr. 18, 434–444. https://doi.org/10.1016/j.jtrangeo.2009.08.004.

Meza, A., Ari, I., Al-Sada, M.S., Koç, M., 2021. Future LNG competition and trade using an agent-based predictive model. Energy Strateg. Rev. 38, 100734 https://doi.org/10.1016/j.esr.2021.100734.

Meza, A., Koç, M., 2021. The LNG trade between Qatar and East Asia: potential impacts of unconventional energy resources on the LNG sector and Qatar's economic development goals. Resour. Policy 70, 101886. https://doi.org/10.1016/j.resourpol.2020.101886.

Meza, A., Koç, M., Al-Sada, M.S., 2022. Perspectives and strategies for LNG expansion in Qatar: a SWOT analysis. Resour. Policy 76, 102633. https://doi.org/10.1016/j.resourpol.2022.102633.

Miah, M.A., Ahmed, S.M.S.U., Sultana, K.S., 2019. Control over maritime chokepoints an assurance of secure lifeline. Bangladesh Marit. J. 3, 109–128.

Muller, N., 2019. Nicaragua's Chinese-financed canal project still in Limbo. Dipl.

Muravev, D., Hu, H., Rakhmangulov, A., Mishkurov, P., 2021. Multi-agent optimization of the intermodal terminal main parameters by using AnyLogic simulation platform: case study on the Ningbo-Zhoushan Port. Int. J. Inf. Manage. 57, 102133 https://doi.org/10.1016/j.ijinfomgt.2020.102133.

Narula, K., 2019. Maritime Security and Its Role in Sustainable Energy Security. Springer Singapore, pp. 117–142. https://doi.org/10.1007/978-981-13-1589-3_6.

Neumann, A., Ruster, S., Hirschhausen, C.von, 2015. Long-term Contracts in the Natural Gas industry: Literature Survey and data on 426 Contracts (1965-2014). Berlin, Germany.

Notteboom, T.E., 2012. Towards a new intermediate hub region in container shipping? Relay and interlining via the Cape route vs. the Suez route. J. Transp. Geogr. 22, 164–178. https://doi.org/10.1016/j.jtrangeo.2012.01.003.

Rodrigue, J.P., 2004. Straits, passages and chokepoints. A maritime geostrategy of petroleum distribution. Cah. Geogr. Que. 48, 357–374. https://doi.org/10.7202/011797ar.

Schach, M., Madlener, R., 2018. Impacts of an ice-free Northeast Passage on LNG markets and geopolitics. Energy Policy 122, 438–448. https://doi.org/10.1016/j.enpol.2018.07.009.

Schøyen, H., Bråthen, S., 2011. The Northern Sea Route versus the Suez Canal: cases from bulk shipping. J. Transp. Geogr. 19, 977–983. https://doi.org/10.1016/j.jtrangeo.2011.03.003.

Steuer, C., 2019. Outlook For Competitive LNG Supply. OIES paper: NG 142.

Tereshin, A.G., Klimenko, A.V., Klimenko, V.V., 2015. Golden age of gas and its impact on the world energy, the global carbon cycle and climate. Therm. Eng. 62, 311–321. https://doi.org/10.1134/S0040601515050122.

The Maritime Executive, 2017. Expanded Panama Canal Operational for a Year. Marit. Exec.

U.S.Department of Energy, 2018. Global LNG Fundamentals. Understanding Natural Gas and LNG Options.

Vivoda, V., 2010. Evaluating energy security in the Asia-Pacific region: a novel methodological approach. Energy Policy 38, 5258–5263. https://doi.org/10.1016/j.enpol.2010.05.028.

Von Hippel, D., Suzuki, T., Williams, J.H., Savage, T., Hayes, P., 2011. Energy security and sustainability in Northeast Asia. Energy Policy 39, 6719–6730. https://doi.org/10.1016/j.enpol.2009.07.001.

Willenski, U., Rand, W., 2015. An Introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with NetLogo. The MIT Press, Cambridge, United Kingdom.

Yip, T.L., Wong, M.C., 2015. The nicaragua canal: scenarios of its future roles. J. Transp. Geogr. 43, 1–13. https://doi.org/10.1016/j.jtrangeo.2015.01.002.

Zhang, Z.X., 2011. China's energy security, the Malacca dilemma and responses. Energy Policy 39, 7612–7615. https://doi.org/10.1016/j.enpol.2011.09.033.