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Panama Canal expansion: Will Panama Canal be a game changer for LNG exports to Asia?

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Abstract: The expansion of the Panama Canal will be completed by 2015. The route via the Panama Canal will shorten voyages from North America to Japan by more than 7,500 nautical miles. However, the competition for use of the Canal is high because it is a major route for container ships and other vessels including crude oil, metal ores, and other materials. Therefore several questions have been raised regarding how much the capacity of the Panama Canal will be available for LNG passages as well as how much LNG will go through the Canal. Applying the 2014 World Gas Model, this paper investigates the influence of the Panama Canal capacity level for LNG tankers on global gas markets and LNG exports from the Gulf of Mexico via five scenarios. The model results show that without the Panama Canal route with its expanded capacity, it is unprofitable to export LNG from the Gulf of Mexico to Asian markets. In addition, when Panama Canal capacity is limited, the U.S. becomes a swing LNG exporter who supplies both Asian and European markets.

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1 Introduction

The Panama Canal is a major waterway connecting the Atlantic and Pacific Oceans and accommodates more than 14,000 transits per year (Canal de Panama, 2012). However, the Panama Canal is not a significant feature of the liquefied natural gas (LNG) market. Only 21 of the 370 LNG tankers worldwide currently in operation can pass through the Panama Canal, but none of these tankers have done so because LNG tankers have special containment systems that require larger and deeper waterways (Alaskan Natural Gas Transportation Project, 2012). Nonetheless, the canal expansion, which is expected to be completed by 2015, could allow more than 80% of LNG tankers to use the waterway. The newly upgraded canal will provide a shorter distance for LNG trade between the Atlantic and Pacific basins and thus could change the landscape of the global LNG trade. In particular, the Panama Canal will allow for LNG trade between the two basins at lower transportation costs due to decreased shipping distances. In light of the anticipated upgrades, the impact of the expanded Panama Canal on global LNG trade, especially on U.S. LNG exports, has been asked.

Recently, hydraulic fracturing and horizontal drilling enabled the gas extraction from shale formation economically. In fact, shale gas production in the U.S. increased fivefold from 2006 to 2010. Furthermore, shale gas accounted for 23% of the total U.S. natural gas production in 2010 (EIA, 2011). The increase in domestic natural gas production has depressed domestic natural gas prices and has caused a large disparity between gas prices in the U.S. and those elsewhere in the world. In the near future, the U.S. will not only be gas self-sufficient but may also be an LNG exporter. As a result, several natural gas producers are eager to apply for natural gas export licenses (Ratner, 2015).

The U.S. is more attractive and favorable than other LNG suppliers for several reasons. First, because of the negative effects of Russian-Ukrainian gas disruptions in the past, U.S. LNG would be considered as an alternative for increasing supply security and energy independence in Europe due to the close proximity of the U.S. to Europe. Likewise, Asian LNG buyers, such as Japan, South Korea, and India, aim to diversify their suppliers. U.S. LNG will increase the security of supply in Asia. Second, U.S. LNG sources are more reliable due to the political stability of the country compared to other exporters, such as African producers. For example, supplies have been interrupted by political instability in Egypt (EIA, 2013; Ernst & Young, 2012). Third, several prominent LNG exporters, such as Indonesia and Malaysia, have decreased their output over time, prompting LNG consumers to search for new LNG sources, especially because many existing long-term contracts will end between 2014 and 2016. Lastly, North American LNG pricing is based on hub prices, which recently are lower than traditional oil index prices. As a result, U.S. LNG exports could affect global LNG prices and could bring more competition to global LNG markets. Moreover, some countries might benefit from U.S. LNG exports, while others might be disadvantaged.

The U.S. Department of Energy (DOE) has granted several NON-FTA licenses allowing natural gas companies to export gas globally (DOE, 2013). As of October 2013, the total U.S. LNG export capacity to NON-FTA countries was 57.8 Bcm/y; of that capacity, 55.6 Bcm/y comes from liquefaction plants in the Gulf of Mexico and 2.2 Bcm/y comes from plants located on the East Coast. Additional export applications with a total capacity of 279 Bcm/y are under consideration by the DOE. Due to these export capacities and lower gas prices, the U.S. will be more competitive in future LNG markets. Moreover, experts believe that the Panama Canal widening will improve the competitive position of LNG exports from the U.S. Gulf Coast and provide buyers in Asia with more opportunities to source supply. However, questions remain regarding how much LNG will flow through the canal, who will use the canal, and who will be positively and negatively impacted by the new route option given unknown capacity and pricing allocated for LNG shipping.

The aims of this paper are to investigate the effects of the Panama Canal capacity level for LNG shipping and LNG exports from the Gulf of Mexico. This paper also analyzes the impact on LNG shipping economics as well as impacts on global gas prices. In particular, this paper identifies how much LNG will flow through the Panama Canal given different capacities, who will use the Panama Canal, and what will be the advantages and disadvantages of the expanded capacity of the Panama Canal. Using a mixed complementarity problem (MCP) market equilibrium approach, the 2014 World Gas Model (WGM) provides insightful results for natural gas production levels, consumption, prices, and future expansions of natural gas infrastructure

capacity given different market conditions. The results offer policy planning officials and decision makers a better understanding of future LNG markets.

Recently, several equilibrium models have been developed to describe the structure of international gas trade. Some of these models cover specific regional trades (e.g., Europe and North America), including GAMES (Abada et al., 2013), GASTALE (Lise and Hobbs, 2009), GASMOT (Holz et al., 2008), (Gabriel et al., 2005a, 2005b), and (Gabriel et al., 2003). In addition, the FRISBEE model (Aune et al., 2009; Rosendahl and Sagen, 2009), the Rice World Gas Trade Model (RWGTM) (Rice University, 2004, 2005), the World Gas Model (Gabriel et al., 2012) depict the global gas trade. Some of these models, such as GASTALE, GASMOT WGM-2010, and WGM-2012, include LNG markets, but none account for the limitations of maritime shipment. In fact, transportation is a major component of LNG trade. The COLUMBUS model (Hecking and Panke, 2012) considers the transportation limitations of LNG shipping; however, it assumes only one route between each liquefaction and regasification site pair, and the shipping cost is determined exogenously.

In addition, there is a previous study related to the influence of Panama Canal expansion on the global gas market. The work by (Moryadee et al., 2014) used the WGM-2012 (Gabriel et al., 2012) to investigate the impact of Panama Canal tolls on the global LNG market. However, Moryadee et al. (2014) assumed only one route was available (least distance) for each liquefaction and regasification node. Furthermore, that study distinguished each scenario only by changing distances and shipping costs. Lastly, that study assumed unlimited shipping capacity for LNG tankers as well as unlimited capacity for the Panama Canal. However, in reality LNG tankers need to compete with other ships for the use of the Panama Canal. Moreover, the new lock of the Panama Canal, which is available for large size ships, can accommodate only 15 passages per day. This might be a constraint for LNG shipment between two basins.

To address the limitations of the previous studies, we present WGM-2014, an extension of WGM-2012 (Gabriel et al., 2012). WGM-2014 incorporates more realistic elements to LNG markets. The WGM-2014 takes into account the limitation of canals and restrictions on tanker capacity by modeling the canal operator and LNG shipping operator as separate market agents. In addition, WGM-2014 endogenously computes the tolls for both the Panama and Suez Canals as opposed to exogenously fixing them in WGM-2012 (Gabriel et al., 2012). Also, WGM-2014 includes three types of LNG tankers; small ($\leq 140,000 \text{ cm}^3$), large ($\leq 170,000 \text{ cm}^3$), and extra-large ($\geq 170,000 \text{ cm}^3$) while WGM-2012 has no tankers modeled. Lastly, WGM-2014 endogenously determines shipping costs, but WGM-2012 has exogenous shipping costs.

These modeling improvements resulted in more realistic LNG trade flows. For example, the total LNG trade was only about 1.2% off from historical values for 2010; WGM 2012 (Gabriel et al., 2012) is approximately 30% off. More details of WGM 2014 are discussed in Section 3.1 and the mathematical formulation is presented in Appendix A. WGM-2014 was originally based on the works (Gabriel et al., 2005a), (Gabriel et al., 2005b), and (Gabriel et al., 2012). All these versions were developed in mixed complementarity formats, where the Karush-Kuhn Tucker (KKT) conditions of individual gas market players are both necessary and sufficient, see Appendix B.

The remaining portion of the paper is organized as follows: Section 2 provides a literature review of issues related to the global LNG trade, LNG shipping, and the Panama Canal expansion. Section 3 describes the study method and the input data. Section 4 proposes scenarios involving U.S. LNG exports and the Panama Canal. Section 5 presents the results and the analysis, and Section 6 provides conclusions and describes future work.

2 Global LNG trade, LNG shipping cost, and the Panama Canal expansion

2.1 Global LNG trade

Unlike oil and coal, due to the gaseous nature of natural gas, before the development of LNG technology, transportation of natural gas was limited by pipeline and was costly due to the low density property.

Moreover, there was substantial infrastructure investment needed to transport natural gas from supply to demand points. The evolution of LNG has considerably changed all that and enabled the use of maritime transportation so that gas can be shipped and traded internationally. However, LNG has historically been a regional fuel with most LNG trade made within the same basin where it is produced (GIIGNL, 2013). For example, LNG Trade Data for the period 1995–2012 indicates that suppliers in both the Atlantic Basin and Asia/Pacific regions dedicated over 99% of their supply to markets in the same basin. Before the 2010 nuclear disaster in Japan, the difference in the price of gas between Asia and Europe was small, approximately \$0.50 (BP, 2013) and this price difference could not cover high shipping costs so that LNG trade between basins was uneconomical. Nonetheless, the price divergence between the basins has increased since mid-2010 due to strong demand in Asia, especially Japan. In 2012, according to BP Statistical Reviews (2013) natural gas price prices were \$16.75/MMBtu in Japan¹ but only \$9.70/MMBtu in Europe (Heren NBP index) and \$2.75/MMBtu in the U.S. (Henry Hub). Therefore, exporting LNG between basins became cost effective depending on the shipping costs.

2.2 LNG shipping cost

LNG shipping costs involve three main elements: the LNG carrier’s capital, the operating cost, and the voyage cost, i.e., marine fuel cost. The capital cost is considered a fixed cost, while the operating and voyage costs are variable. The operating cost includes manning, maintenance, and insurance. LNG projects require large investments. A new standard-size LNG tanker (170,000 m³) costs more than \$200 million USD to build because it requires costly materials and sophisticated cargo-handling equipment (Petroleum Economist, 2011). Because LNG tankers are sophisticated ships, they require specialized crews. As a result, the manning costs are high, accounting for 35% of the operating cost (Petroleum Economist, 2011). The majority of the voyage cost is associated with fuel and port costs. The fuel cost is based on the speed and engine performance, whereas the port costs depend on the destination port; they can be complex and variable depending on the size and volume of the tanker. In addition, the voyage cost also includes transit fees, such as canal tolls. Because the capital cost is fixed, the main variable cost is the voyage cost, which depends on the distance of the trip. Table 1 shows the shipping costs in \$/MMBtu from various locations to Tokyo, Japan based on data from IHS CERA (Reuters, 2013). The shipping cost from the Atlantic Basin to Japan is three to four times higher than that for the Pacific Basin. However, the Panama Canal route will significantly reduce the time and shipping cost of transportation between the two basins.

Table 1: Shipping cost per million Btu in 2012 from various locations to Tokyo, Japan

Route	Shipping cost
Indonesia–Tokyo	less than \$1/MMBtu
Australia–Tokyo	\$1.22
Trinidad & Tobago–Tokyo	\$4.16
Norway–Tokyo	\$4.13
North Africa–Tokyo	\$3.26
USA (Gulf of Mexico)–Tokyo	\$4.40

Because a significant portion of the voyage costs depend on the fuel, which is a function of the distance, the presence of the Panama Canal will reduce the voyage costs from the Atlantic Ocean to the Pacific Ocean. IHS CERA (Reuter, 2013) estimated that the route via the Panama Canal will reduce the shipping cost from the Gulf of Mexico to Japan by approximately \$1.50/MMBtu. However, at the time of this research, the Panama Canal Authority has not determined what toll it will charge LNG tankers to pass through the canal, so the final toll could differ. IHS CERA assumed a toll of \$0.30/MMBtu based on a \$1 million round-trip fee for a medium-sized LNG tanker, which leaves a significant savings of \$1.20/MMBtu. Regardless of the toll, the larger canal will improve the economics of LNG shipping between the two basins and will create incentives to exploit pricing differences between the Pacific and Atlantic markets. The price difference between the basins might be narrowed and may benefit Asian consumers.

¹Japan LNG prices include cost + insurance + freight (average cost).

2.3 Panama Canal expansion

The Panama Canal is currently restricted to vessels with beams² of less than 32 meters, 294-meters long, with draft³ of no more than 12 meters (see, Table 2) (Panama Canal Authority, 2010). The expansion of the Panama Canal will allow for the first time, large tankers with beams up to a maximum of 49 meters to pass. When the expansion is finished, at least 80 % of the LNG tankers, up to large LNG conventional ones (up to 180,000 m³), operating in 2013 will be able to use the waterway except for Q-Flex (209,000–216,200 m³) and Q-Max (260,000–266,000 m³) size tankers. Consequently, the distance to transport U.S. LNG from the Gulf of Mexico will decrease from 16,000 miles to approximately 9,700 miles, reducing the travel time from the U.S. Gulf Coast to Tokyo, Japan from 41 to 25 days. Also, the route can reduce time going from east to west e.g., Peru–Brazil. The comparison of distances in different routes is shown in Table 3.

Table 2: Maximum allowed containership dimension before and after expansion in meters (m) and dimensions for large conventional LNG carriers

	Maximum dimension before expansion	Maximum dimension after Expansion	Dimensions for large conventional LNG carriers (150,000–180,000 m ³)
Length overall	294.30 m	366.00 m	285.00–295.00 m
Draft	32.31 m	49.00 m	43.00–46.00 m
Beam	12.04 m	15.24 m	Up to 12.00 m

(Man Diesel and Turbo, 2011)

Table 3: Comparison of distances (nautical miles⁴) between ports

Origin	Destination	Via Panama Canal	Via Suez Canal	Around Cape Horn	Around Good Hope
Gulf of Mexico	Western Mexico	3,733	21,637	9,783	19,713
	Chile	4,449	19,723	13,476	20,266
	Japan	9,756	14,449	17,060	15,697
	Singapore	12,147	11,910	16,900	13,157
Trinidad & Tobago	Western Mexico	3,331	20,272	7,643	17,573
	Chile	4,048	18,358	11,336	18,126
	Japan	9,355	13,054	14,920	13,557
	Singapore	11,746	10,545	14,761	11,027
Norway	Western Mexico	7,471	19,474	10,801	19,601
	Chile	8,188	17,559	14,493	20,155
	Japan	13,494	12,285	18,078	15,585
	Singapore	15,886	9,746	17,918	13,046

Source: (Popils, 2011)

Currently, the Panama Canal authority operates with two lanes of locks that can handle ships at near its capacity or about 35 ships per day. The expansion of the Panama canal includes two new sets of locks—one on the Atlantic and one on the Pacific side. Each new lock will have three chambers, and the canal itself will be deepened and widened. Recently, congestion is growing and affecting the total passage time. In the peak demand period, some container ships need to wait one day or longer to enter the canal. After expansion, the new third set of locks will help eliminate some of those backlogs, by adding perhaps 15 passages to the daily total. However, the capacity for LNG transit is still possibly an issue. The priority for the canal booking system is complicated, including ship characteristics, load type, and daylight restriction. Moreover, LNG tankers need to compete with other ships to use the canal.

²Beam – the greatest width of a nautical vessel.

³Draft – the distance between the vessel's waterline and the lowest point of the vessel.

⁴The nautical mile equals 1,852 meters exactly (about 6,076 feet).

3 Study methods and input data

This section presents the framework used to determine the impact of the Panama Canal capacity level on LNG exports from Gulf of Mexico in particular and global gas markets in general. The structure of the LNG and shipping markets are identified. Because LNG transportation, including the shipping cost and capacity, is a major component of the market, its impact on the patterns of exports from Gulf of Mexico is analyzed.

3.1 The World Gas Model

In the previous version of WGM, WGM-2012 (Gabriel et al., 2012), the market agents include natural gas producers, traders, storage operators, an integrated pipeline and system operator, and marketers. The traders are modeled as strategic players and coordinate both pipeline and LNG flows from the same country. Unlike WGM-2012, WGM-2014 includes additional details on the LNG markets and accounts for the limitations of maritime transportation on these markets (e.g., LNG carrier capacity, LNG shipping routes, and congestion in shipping routes). In this framework, the authors integrated the shipping markets as part of the LNG markets with endogenously determined prices by tanker category. Therefore, the model includes additional market participants, namely liquefiers, regasifiers, LNG transportation operators, and canal operator. All these new players are modeled by separate optimization problems to account for important constraints, such as capacity as well as future investment decisions see Appendix A for more details. WGM 2014 has 5-year periods starting in 2005 and continuing through 2060; each “year” has high and low demand seasons. In terms of LNG contracts, the authors incorporate LNG contract data base from GIIGNL (2014) and assume that the contracts will be renewed with the same value after they expire.

In WGM-2014, LNG transportation operators have the ability to propose LNG flows for three routes: via the Suez Canal, via the Panama Canal, and via a normal route without canals from the liquefaction node to the regasification node. The actual flows are determined by the equilibrium condition for all players. LNG can be shipped over shorter distances through these canals with an extra charge (toll) or over the normal route with longer distances but no toll. The LNG tankers in this model are considered in terms of their aggregate capacity rather than individually for computational reasons. For simplicity, it is assumed that there are three LNG transportation operators own tankers of different sizes, small ($\leq 140,000 \text{ cm}^3$), large ($\leq 170,000 \text{ cm}^3$), and extra-large ($\geq 170,000 \text{ cm}^3$) e.g., Q-Max and Q-Flex, with different aggregate capacities, future investment costs, and operating speeds. The size the LNG tankers is important because each type of tanker has different operating costs, and extra-large tankers cannot use Panama Canal due to size limitations. In this study, it is assumed that the LNG buyers are responsible for the LNG shipping charges, which come from market-clearing conditions between the regasifiers and the LNG transportation operators for each origin-destination pair. This shipping service charge was exogenous in WGM-2012 but in WGM-2014 is endogenously determined for greater realism. Since the Panama Canal already has other users, the capacity available to LNG is a user defined maximum capacity of the expanded Canal.

Another adjustment that is relevant to LNG markets is that the canal operator is modeled. The authors assume that the canal operator owns two main canals, the Panama and Suez Canals, for LNG shipping. The canal operator collects transit fees for providing shorter routes, and congestion fees at the canal are imposed when the waterway is busy with traffic. Lastly, all of the market participants except for the canal operator have endogenous future investments. Appendix A provides the complete mathematical formulations and assumptions for each market player, and Appendix B describes the associated KKT and market-clearing conditions. Details of the input data for WGM-2014 are shown in Table 4 and Figure 1 shows a representation of the LNG market in WGM-2014.

It is important to note that for many existing LNG users, particularly in Asia, gas and oil compete for a considerable portion of the market, unlike the U.S. where gas and oil markets are weakly linked. That implies that with greater amounts of economic gas available to those markets, the demand for natural gas could significantly increase, thereby reducing the demand for oil. Since contract prices for LNG to Asia are often linked to the world oil price, greater use of US natural gas could also reduce the LNG contract prices to those markets. Since the WGM does not currently capture the oil-gas interactions, this aspect of the energy market is currently not modeled but may be a topic for future enhancement.

Table 4: Market agents and input data in WGM 2014

Market agents	Input data and references
Producers	Production cost function (Golombeck et al., 1995, 1998) Production reference (EIA,2013; IEA,2011)
Storage operator	Storage capacity (EIA, 2007; GSE, 2008) Storage expansion <i>Oil and Gas Journal</i>
An integrated pipeline and system operator	Pipeline capacity (GTE, 2005, 2008) Pipeline transportation cost (Oostvoorn , 2003) Pipeline expansion <i>Oil and Gas Journal</i>
LNG transportation operators	Shipping capacity (GIIGNL, 2013) Average speed (MAN Diesel & Turbo, 2011) Shipping cost (Petroleum Economist, 2011) LNG shipping distance (PortWorld.com)
Canal operator	Canal toll (Petroleum Economist, 2011)
Liquefiers	Liquefaction capacities (GIIGNL, 2013)
Regasifiers	Regasification capacities (GIIGNL, 2013) LNG contact database (GIIGNL, 2013)
Marketer	Consumption reference (EIA,2013; IEA, 2011) Reference prices (IGU, 2013)

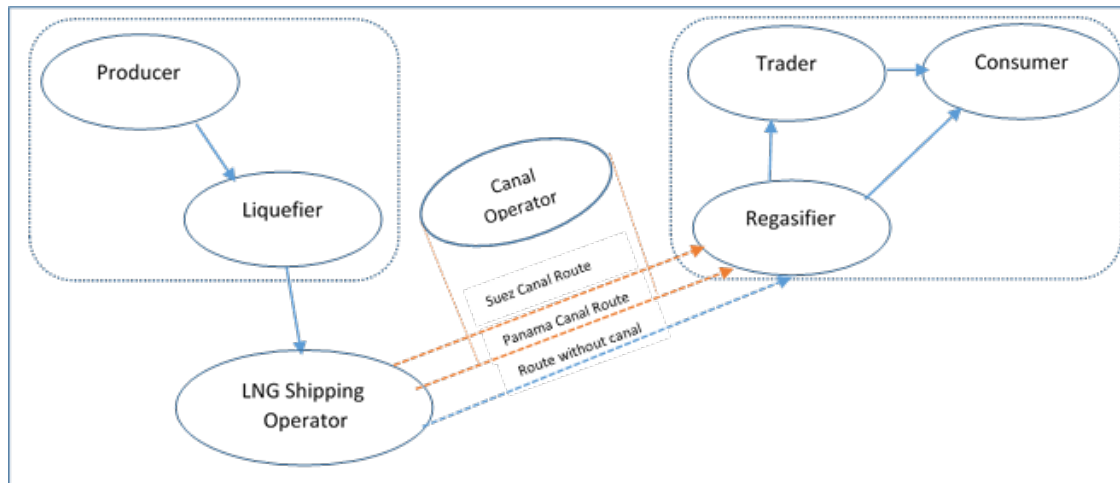


Figure 1: Representation of the LNG market in WGM-2014

The current version of the model is composed of 42 nodes that represent individual or aggregated countries and covers 98% of the worldwide consumption and production for 2010. On the supply side, the WGM also characterizes three types of producers in each region of the U.S.: conventional gas, shale gas, and non-shale unconventional gas. The model operates in five-year periods from 2005–2050 as well as in high and low demand seasons. The year 2010 is used as a calibration year. On the LNG side, WGM-2014 consists of 15 aggregated liquefaction nodes and 23 regasification nodes and covers more than 85% of the actual long-term contracts that were in place in 2010. In addition, LNG spot markets are used to investigate the state of the global gas market. The model solves for decision variables, including the operating levels (e.g., production, storage injection) and capacity investments (e.g., for pipelines and liquefaction). A total of 103,000 variables make up the WGM complementarity system, which can be solved on a standard personal computer (e.g., 4 GB of RAM and 1.2 GHz clockspeed) in approximately 240 minutes.

4 Scenarios

This section describes the scenarios defined in this study. First, we define the Base Case as the baseline for the comparisons with the other scenarios. The Base Case assumes no Panama Canal route and no U.S. LNG exports. Secondly in term of US LNG exports for the rest of scenarios this study assumes the U.S. exports LNG from the Gulf of Mexico with a capacity of 57.88 Bcm/y, 8.25 Bcm/y from the West Coast, and from the East Coast at 10.33 Bcm/y. Only 4.5 Bcm/y from the Gulf of Mexico is under long-term contract with specific destinations (from the U.S. to India), so the rest of the capacity is endogenously determined by the model and thus corresponds to the LNG spot market.

The authors assume the U.S. starts exporting LNG with a capacity of 57.88 Bcm/y in 2015.⁵ In addition, the U.S. has the ability to expand its export capacity by 50 Bcm⁶ during each five-year time period. Lastly, there is an assumption the Panama Canal capacity regarding the competition for canal capacity. The new lock of the Panama Canal will add approximately 15 passages to the daily total (Fountian, 2011). Since no LNG tankers can make it through the Panama Canal due to insufficient lock depth, this means the Panama Canal capacity will vary from 0 to 15 passages for LNG given the other users of the Canal. Since WGM-2014 provides a market equilibrium for global natural gas markets, it only considers LNG tankers for the use of the Panama Canal. Other competition for the Canal, e.g., crude oil, metal ores, agricultural products, and other materials are not directly represented. Therefore, this study estimates the capacity for LNG shipping using the number of LNG vessels transiting through the Panama Canal via four choices of Canal capacity (zero, low-100 ships per year, medium-200 ships per year, high-250 ships per year), assuming the largest sizes of tankers (170,000 m³) passes through the Canal.⁷ The scenarios descriptions are as follows:

1. The Base Case is run without the Panama Canal route and with no U.S. LNG exports. The Base Case consumption outcome uses the data sources presented in Table 4 and is calibrated to multiple sources. Details of this calibration are provided in the next section.
2. The second scenario considers U.S. exports as previously discussed without the Panama Canal route and is denoted as “USLNG_Panama0”.
3. The third scenario, which is abbreviated “USLNG_Panama100”, uses the same assumptions for the U.S. Exports, but the route via the Panama Canal is available starting in 2015 with endogenously determined transit tolls from market-clearing conditions. The authors estimate the maximum capacity of the Panama Canal by assuming that up to 170,000 m³ capacity ships with an estimated 100 LNG vessels transiting through the Panama Canal each year once the expansion is completed.
4. The fourth scenario, which is abbreviated “USLNG_Panama200”, uses the same assumptions as USLNG_Panama100 on the U.S. LNG exports and the availability of the Panama Canal, but assumes that the Canal can accommodate up to 200 LNG tankers of 170,000 m³ each year.
5. The last scenario which is abbreviated “USLNG_Panama250”, uses the same assumptions as USLNG_Panama100 but assumes that the Canal can accommodate up to 250 LNG tankers of 170,000 m³ each year.

The five scenarios were first simulated up to 2035 and allowed for an analysis of the flows of U.S. gas exports in the global market. The global results, including production and consumption, are presented in the next section.

⁵The U.S. is expected to start LNG exports from Cheniere Energy terminal in 2017, but we assume the U.S. starts earlier in 2015 due to the five-year time steps in the model.

⁶The capacity investment cannot be realized instantaneously by the model. WGM has five-year time steps which are enough for the time lag for construction. In this case, the U.S. can increase its export capacity over the time horizon if it is profitable.

⁷Although there are 393 LNG vessels in operation (GIIGNL, 2013), only 90% can pass through the Panama Canal. Of these 393 ships more than 80% are already committed under long-term for specific routes that do not use the Panama Canal.

5 Results

5.1 Model validation and the calibration results

The consumption output of the base case was calibrated to match the global natural gas markets in 2010 provided by the 2013 BP Statistical Review as well as projections from multiple sources. The model outcome for the U.S. considers the rapid growth of shale gas development in the next decades. The U.S.'s natural gas consumption and production are specifically calibrated according to the forecast from the Annual Energy Outlook (EIA, 2013). The production and consumption for the rest of the world is based on the World Energy Outlook (IEA, 2011): New Policy Scenario as a reference, which takes into account rapid growth rates for demands in Asia and the Middle East. For LNG markets, GIIGNL (2011) is a valuable source for natural gas liquefaction and regasification capacities and long-term contracts.

The Base Case is used as the baseline for comparison against other scenarios. To examine the error of the model, the authors compare its output to historical references. As shown in Table 5, the consumption results in 2010 for the Base Case differ slightly from the reference (BP, 2013). The percentage differences in Table 5 are the BP 2013 values minus the WGM values divided by the BP 2013 values. The difference between the WGM consumption and the BP values (2013) is less than 5%. The authors separate Japan/S. Korea from the Asia Pacific region because this paper primarily focuses on the LNG market, of which Japan has the highest consumption in the world. Among the remaining regions, North America has the highest consumption while Asia Pacific, Europe, and the Former Soviet Union have intermediate levels of consumption.

Table 5: Comparison of natural gas consumption in 2010 from the WGM output and BP (2013) (Bcm)

	WGM	BP (2013)	% difference
AFRICA	102.9	107.8	4.55%
ASPACIF	371.7	387.1	3.98%
EUROPE	537.1	544.6	1.38%
FRSVTUN	580.2	585	0.82%
JAPAN/S. Korea	144.3	137.5	-4.95%
MIDDLE EAST	339	329	-3.04%
NRTHLAM	774	767	-0.91%
STHAM	134.5	132.9	-1.20%

Table 6 indicates that the total LNG trade in 2010 calculated by WGM-2014 is 272.1 Bcm/y, while the actual trade from GIIGNL was 275.54 Bcm/y. The percentage differences between the GIIGNL (2011) and WGM figures of LNG global trade for 2010 are fairly small. Asia was the dominant LNG importer in 2010, whereas the largest LNG sources are from the Pacific Basin, supplied by Australia, Indonesia, and Malaysia.

Table 6: LNG imports by region and source of imports in 2010

LNG imports by region in 2010 (Bcm)				Source of imports in 2010 (Bcm)			
	WGM	GIIGNL (2011)	Difference		WGM	GIIGNL (2011)	Difference
Europe	84.9	81.63	4.0%	Atlantic Basin	74.7	79.44	5.97%
Americas	25.6	26.3	2.7%	Middle East	89.8	93.47	3.93%
Asia	161.6	164.87	2.0%	Pacific Basin	107.6	102.63	4.84%
Middle East ⁸	–	2.75	–	Total	272.1	275.54	1.25%
Total	272.1	275.54	1.2%				

In terms of the projected regional consumption, the results of WGM-2014 display the same trend as the Annual Energy Outlook (IEA, 2013) for the U.S. and the World Energy Outlook (IEA, 2011) for the rest of the world, as shown in Figure 2. The Asia Pacific region has the highest growth rate from 2010–2035. The consumption of the rest of the world gradually increases after 2015. By the end of 2025, the world's natural gas consumption will reach approximately 4,000 Bcm/y, of which approximately half will come from the Asia

⁸The WGM does not combine Kuwait and Dubai as an aggregated node.

Pacific region, the Former Soviet Union, and North America. The results are predicated on the IEA and EIA results for gas demands. However, those gas demands could change substantially depending on the related world oil price assumptions.

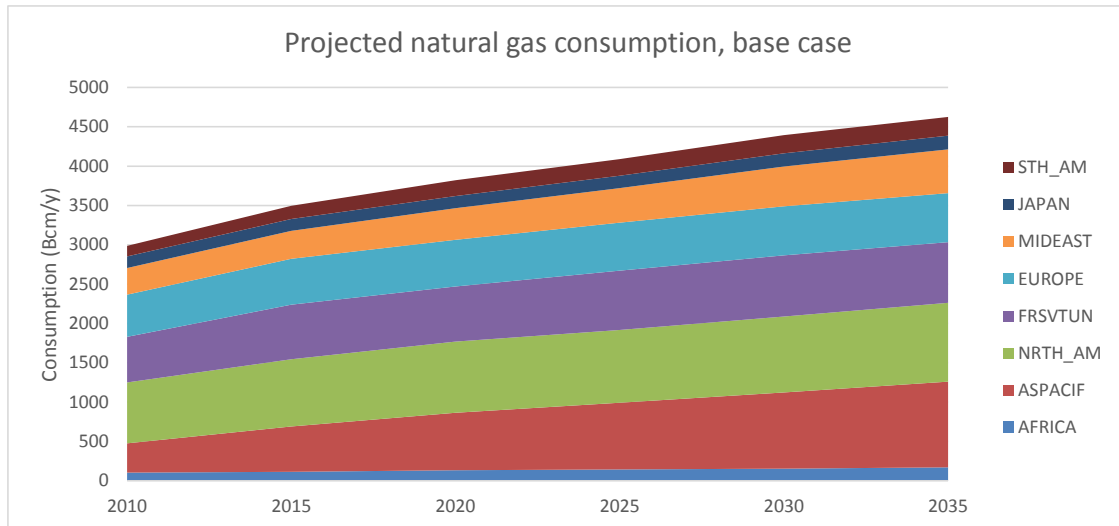


Figure 2: Projected natural gas consumption for the base case

5.2 Impact of LNG shipping economics

The overall impact of the canal expansion on LNG trade is fairly obvious: shorter distances and voyages lower the shipping costs. What is not so obvious and what was in part the motivation for this study, was the effect on particular shipping patterns (who gets more LNG), resulting regional prices, and other specific results.

In general, shorter distances reduce fuel consumption and LNG boil-off. Shorter voyages reduce the charter period⁹ for voyages and increase vessel utilization since the route via the Panama Canal reduces the turnaround times per trip, more shipping capacity turns into availability, and this should improve the total LNG trade. We found that these hypotheses are true if there is enough capacity of the waterway for LNG shipping. The first thing to realize is that the total LNG trade over time under the Base Case is less than the rest of scenarios due to the restriction on U.S. LNG exports, see Figure 3.

Next, the difference between USLNG_Panama0 and USLNG_Panama100 scenarios is that there are additional routes via Panama Canal with capacity of 100 ships per year for USLNG_Panama100, but other assumptions for U.S. LNG exports are the same. Figure 3 shows that there is almost no difference in total LNG trade between these two scenarios even though the canal route is available. The explanation is that the U.S. LNG exports to Asia are restricted by the capacity of the Panama Canal, see Section 3 for more details for U.S. LNG export pattern. The conclusion is that the canal capacity is not enough to improve the total LNG trade. However, under USLNG_Panama200 with a capacity of 200 ships per year, the total LNG trade increases 1–3% from 2015–2030 and becomes more pronounced in 2035 as compared to USLNG_Panama100 scenario; the total LNG trade increases by 5% in 2035. Nonetheless, the total worldwide trade is similar for two scenarios, USLNG_Panama200 and USLNG_Panama250, from 2010 to 2030. The total trade increase a little in 2035 (423.4 Bcm v.s. 417.1 Bcm). This indicates that increasing the Panama Canal capacity from 200 ships per year to 250 does not significantly improve the total trade.

The model results in terms of the Panama Canal utilization show that LNG trade becomes more global; the Panama Canal allows the trade from the Atlantic basin to the Pacific basin, and Asian markets rely more on Gulf of Mexico supply. In the past, LNG was usually traded within the same basin because the shipping

⁹How long it takes to travel from the origin (export terminal) to the regasification site.

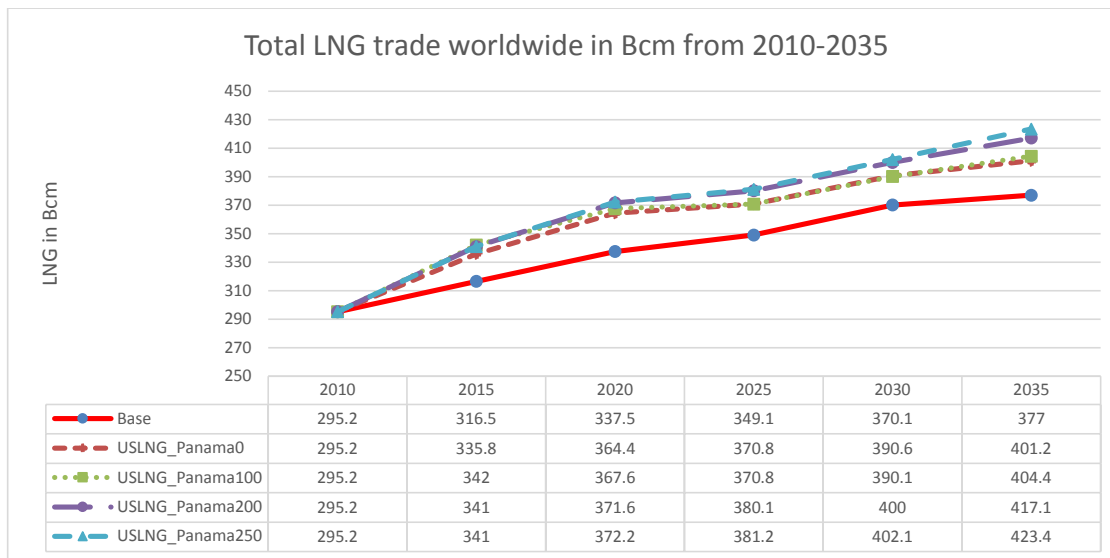


Figure 3: WGM-2014 Total LNG trade in Bcm from 2010–2035¹⁰

cost was too high to ship from one basin to another basin. Figure 4 shows the comparison of the Panama Canal utilization for 2015 and 2035. All of the trade flows from the Atlantic basin to Japan/S. Korea; none flows from the Pacific basin going to the Atlantic. For example, Trinidad & Tobago and the U.S. are the major users of the Panama Canal; they transport 20.8 Bcm and 35.9 Bcm in 2015 via the Panama Canal to Japan under USLNG_Panama100 and USLNG_Panama200, respectively. This phenomenon occurs because Japan/S. Korea has the highest endogenous wholesale prices in the world while the LNG suppliers have profit maximization as an objective. Therefore, exporting gas to Japan can generate a significant profit depending on the shipping cost. In addition, only the LNG from the Gulf of Mexico will benefit from the Panama Canal although there are other Atlantic basin LNG-exporting plants e.g., Snøhvit terminal in Norway and Nigeria LNG and Angola LNG in West Africa. The distances from Snøhvit terminal, Norway, are closer to Asia via the Suez Canal. Likewise, Japan/S. Korea and China are closer to West Africa traveling around the Cape of Good Hope so that no LNG flows through the Panama Canal to China. Moreover, the model results show that there is a considerable gap for Panama Canal utilization when the authors assume 100 ships per year (USLNG_Panama100) and 200 ships per year (USLNG_Panama200), see Figure 4. The utilization difference is less when compared USLNG_Panama200 and USLNG_Panama250. The utilization rate increases as the given canal capacity increases. However, the results for the Suez Canal utilization stays the same for all scenarios, approximately 36 Bcm in 2035. This means increasing Panama Canal utilization rate does not affect the Suez Canal utilization rate and, the flows from Middle East to Europe through the Suez Canal remain the same. In addition, the authors did further analysis by sufficiently increasing the capacity for the Panama Canal e.g., 500 ships per year to see what would be the maximum flows through the Panama Canal. The authors found that the maximum flows reached 68.3 Bcm in 2035 due to the restriction on the gas production and LNG export capacity.

Figure 5 presents the extra-large LNG tanker capacity in 2010 vs. 2035. The model invests in extra-large tankers, even though the investment costs are much higher than that of other tankers. The reason is that extra-large tankers have the lowest unit operating and voyage costs per cm due to the economies of scale of the tankers. It is important to note that the total capacity for extra-large tankers in 2035 decreases when the capacity of the Panama Canal increases, see Figure 5. However, the total LNG trade increases, see Figure 3. This indicates that the Panama Canal route increases efficiency of LNG shipping; less total shipping capacity generates a higher volume of trade. For example, in 2035 when comparing USLNG_Panama100 with USLNG_Panama200, the total capacity for extra-large tanker are, respectively 15.3 million m³ and 11.9 million m³,

¹⁰The reason the total LNG trade drops slightly in 2015 from 342 to 341 Bcm between USLNG_Panama100 and USLNG_Panama200 is presumably due to shifting of supplier market share and non-cooperative, game-theoretic behavior.

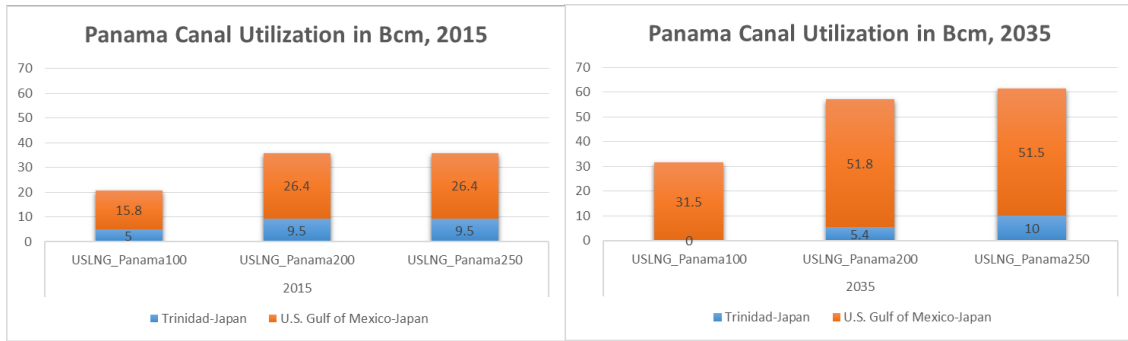


Figure 4: WGM-2014 Panama Canal utilization from 2015 and 2035 Bcm

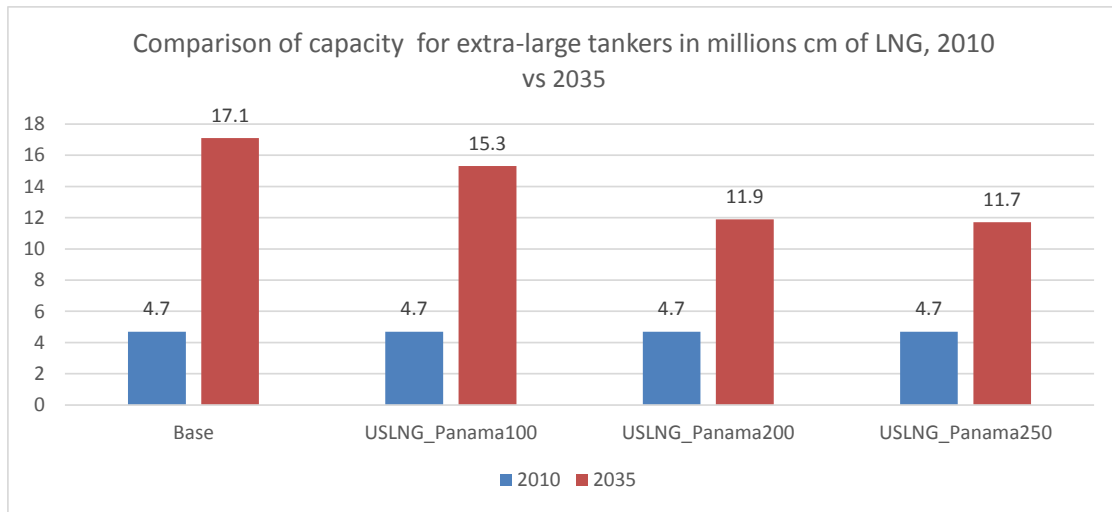


Figure 5: WGM-2014 Comparison of capacity for extra-large tanker in millions cubic meters, 2010 vs 2035

see Figure 5. However the total trade for the same year increases from 404.4 Bcm to 417.1 Bcm, respectively, see Figure 4. The explanation is as follows. Under the USLNG_Panama100 scenario in 2015, the total LNG flow using small tankers is 15.8 Bcm as compared to 36.6 for the USLNG_Panama200 scenario. The total LNG flows for the two other sizes of ships (medium and extra-large) stay the same (extra-large) or almost the same (15.7 vs. 15.2 Bcm for the medium size). In sum, larger Panama Canal capacity (200 vs. 100 ships/year) induces substantially more LNG traded on the smaller ships.

5.3 Impact on LNG exports from Gulf of Mexico

According to the results of our simulations, LNG from the Gulf of Mexico no longer flows to Japan/S. Korea in the absence of the Panama Canal with expanded capacity, but rather transited to Europe. As shown in Table 7, for the year 2015, the U.S. exports scenario without the Panama Canal (USLNG_Panama0), indicates that the U.S. and Trinidad & Tobago will respectively, export 18.4 Bcm and 7.3 Bcm to South America and Europe. Only 4.6 Bcm is transited from the U.S. to India under long-term contract via the Suez Canal. The remainder of the U.S. LNG exports are endogenously determined by the model. Under the USLNG Panama0 scenario the U.S. exports more to Europe (37.6 Bcm) in 2035, see Table 8 as compared to 18.4 Bcm in 2015 in Table 7. Although the U.S. export capacity is approximately 60 Bcm, the total exports do not reach this maximum. This situation shows that the European gas market has limitations in absorbing U.S.-exported LNG. However, the U.S. will export more when the Panama Canal is utilized. In sum, without the expanded Panama Canal capacity, the U.S. will likely export to Europe rather than to Asia because the endogenously determined shipping cost from the Gulf of Mexico to Asia is much higher than that for Europe.

Table 7: LNG Exports from Gulf of Mexico in 2015 (Bcm)

Origin	Destination	Scenarios				
		Base	USLNG Panama0	USLNG Panama100	USLNG Panama200	USLNG Panama250
U.S. Gulf of Mexico	Brazil	0	2.2	0	0	0
	India	4.6	4.6	4.6	4.6	4.6
	Japan/S. Korea	0	0	15.8	26.4	26.4
	France	0	2	1.6	0	0
	Netherlands	0	1.5	0.7	0	0
	Poland	0	2.8	2.8	0.8	0.8
	Spain	0	5	3.5	0	0
	Turkey	0	0.3	0	0	0
	Grand Total	4.6	18.4	29	31.8	31.8
Trinidad & Tobago	Brazil	2.9	2	0	0	0
	Japan/S. Korea	0	0	5	9.5	9.5
	Spain	5.3	5.3	5.3	5.3	5.3
	Grand Total	8.2	7.3	10.3	14.8	14.8

Table 8: LNG Exports from Gulf of Mexico in 2035 (Bcm)

Origin	Destination	Scenarios				
		Base	USLNG Panama0	USLNG Panama100	USLNG Panama200	USLNG Panama250
U.S. Gulf of Mexico	India	4.6	4.6	4.6	4.6	4.6
	Japan/S. Korea	0	0	31.5	51.8	51.5
	France	0	11.5	4.1	0	0
	Netherlands	0	7.5	1.1	0	0
	Poland	0	14.1	5.7	0	0
	The UK	0	4.1	0	0	0
	Spain	0	0.4	0	0	0
	Grand Total	0	42.2	47	56.4	56.1¹¹
Trinidad & Tobago	Japan/S. Korea	0	0	0	5.4	10
	Spain	3	3	3	3	3
	Grand Total	3	3	3	8.4	13

When compared three Panama Canal scenarios (USLNG_Panama100, USLNG_Panama200, and USLNG_Panama250), the level of the Panama Canal capacity also play a significant role for the direction of U.S. LNG exports. USLNG_Panama100 scenario assumes 100 of LNG ships transited through the Panama Canal each year. Under this scenario, the U.S. increases the total exports up to 29 Bcm from 18.4 Bcm (Table 7) in the USLNG_Panama0 scenario and sends 15.8 Bcm to Japan/S. Korea and 8.6 Bcm to Europe (Netherlands, Poland, and Spain) in 2015. With the limited capacity of the Panama Canal in this scenario, the U.S. becomes a swing LNG exporter, sending gas to both east and west. However, when more Panama Canal capacity is available, the U.S. exports almost all of its LNG to Japan/S. Korea. The U.S. exports 26.4 Bcm to Japan/S. Korea in 2015, see Table 7 and 51.8 Bcm to the same destination in 2035 (Table 8) under this scenario. It is important to note that the total endogenous LNG export volume from the U.S. under USLNG_Panama250 is similar to USLNG_Panama200 although the maximum capacity of the Canal goes up to 250 passages/year. It is conventionally thought that when more capacity is available, the U.S. will export more to that market. However, the reverse occurs for U.S. LNG exports. The U.S. exports only approximately 60 Bcm under USLNG_Panama100 and USLNG_Panama250, see Table 8. In the model set-up, the authors allow additional 50 Bcm per year for the expansion of the U.S. Gulf of Mexico terminal in each time period. The terminal can get expanded if it is profitable. The investment condition is that the

¹¹The U.S. sales decrease because Trinidad & Tobago increases its sales to Japan. Trinidad & Tobago has a higher production cost but is closer distance to the Panama Canal (approximately 500 nautical miles closer).

terminal will expand if the total future profit is greater than the cost of current investments as part of the liquefier KKT conditions, see Appendix B, equation B16 for more details. However, there is no investment made by the model for capacity expansion for the U.S. Gulf of Mexico terminal.

5.4 Impact on regional prices

In addition to the impacts discussed above, the importance of the Panama Canal expansion from an LNG market perspective is its influence on global gas price convergence. Lower shipping costs improve the relative economics of shipping Gulf of Mexico gas to Asia. Over time this reduces inter-regional price spreads. Figure 6 and Figure 7 indicate regional price spreads for the USLNG_Panama0 and USLNG_Panama200 scenarios respectively. The price gaps for Japan-Europe and Japan-North America in 2035 are smaller; the difference between Japanese-European prices is \$7.29 for the USLNG_Panama0 scenario (Figure 6), and it is narrowed to \$6.17 (Figure 7) as the Panama Canal route with expanded capacity is employed under the USLNG_Panama200 scenario. Another interesting result is that over time the North American gas prices increase a little under \$6 range due to LNG exports.

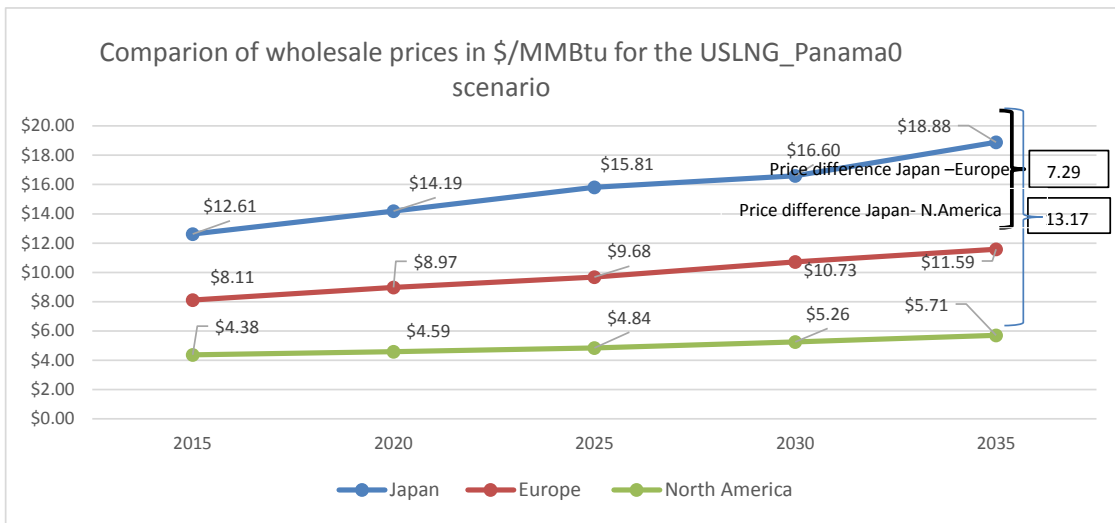


Figure 6: Comparison for wholesale prices in \$/MMBtu for USLNG_Panama0 scenario

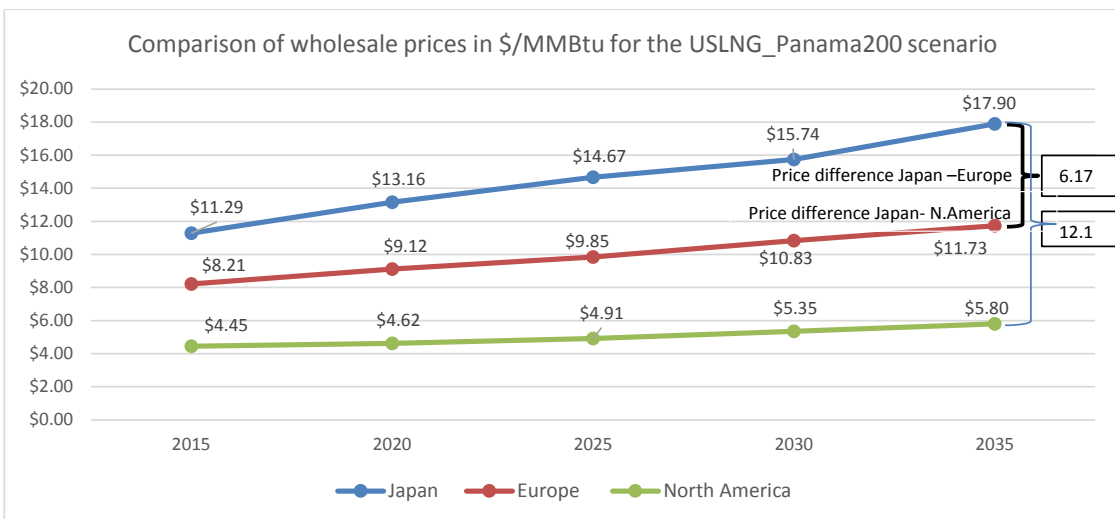


Figure 7: Comparison for wholesale prices in \$/MMBtu for USLNG_Panama200 scenario

In terms of country prices, the U.S. LNG exports caused by the Panama Canal expansion are projected to have other impacts, for example on worldwide prices. Table 9 shows that under the Base Case, the wholesale price in Japan/S. Korea increases to as high as \$18.91/MMBtu in 2035, representing the highest prices among all countries. Southeast Asia/China and India/Pakistan see 2035 prices of \$15.69/MMBtu and \$11.03/MMBtu, respectively. Under the USLNG_Panama0, due to inexpensive U.S. LNG flowing to Europe, the importing countries experience lower gas prices than in the Base Case. The United Kingdom, the Netherlands, Poland, Turkey, and Spain experience reductions of \$0.20–\$0.35/MMBtu in wholesale prices. Due to the availability of the Panama Canal, the wholesale prices in China/Southeast Asia and Japan/S. Korea decrease by \$0.20–0.30/MMBtu under USLNG_Panama100, USLNG_Panama200, and USLNG_Panama250 scenarios as compared to the Base Case (Table 9). Under the same comparison, the prices are also lowered due to more LNG transported by Qatar and Australia although the U.S. does not export gas to China/Southeast Asia. Lastly, when the authors compare the USLNG_Panama0 and USLNG_Panama100 scenarios, the results show that the European prices in the USLNG_Panama0 are higher than in USLNG_Panama100 scenario while Asian prices are in the opposite direction. The explanation is that the expanded Panama Canal allows the exports from Gulf of Mexico to Asia. More gas supplies go to Asia and simultaneously decrease flow to Europe.

Table 9: Wholesale prices in 2035 (\$/MMBtu) for selected country nodes

Country Nodes	Base	USLNG_Panama0	USLNG_Panama100	USLNG_Panama200	USLNG_Panama250
Netherlands	\$11.61	\$11.41	\$11.48	\$11.54	\$11.56
Poland	\$11.97	\$11.59	\$11.82	\$11.83	\$11.85
Spain	\$11.53	\$11.20	\$11.27	\$11.48	\$11.51
Turkey	\$11.29	\$10.95	\$11.05	\$11.20	\$11.21
United Kingdom	\$11.44	\$11.09	\$11.21	\$11.28	\$11.31
China/S.E. Asia	\$15.69	\$15.65	\$15.36	\$14.99	\$14.78
India/Pakistan	\$11.03	\$10.93	\$10.91	\$10.88	\$10.88
Japan/S. Korea	\$18.91	\$18.88	\$18.45	\$17.90	\$17.60

5.5 Other impacts on the global gas market

Without the Panama Canal expanded capacity, under USLNG_Panama0, the entry of U.S. LNG into Europe displaces the market shares of Algeria and Russia in the European LNG markets (Table 10). In 2035, Russia's natural gas flows to Europe decreases significantly from 12.2 Bcm to 0.8 Bcm, and Algeria's flows decreases by approximately 6.1 Bcm under USLNG_Panama0. The WGM results indicate that the greatest effect of the Panama Canal expansion is reflected in the U.S. LNG export pattern, which dynamically changes the market. As shown in Table 10, the U.S. exports 31.5 Bcm and 51.8 of LNG to Japan/S. Korea in the USLNG_Panama200 and USLNG_Panama250 scenarios, respectively compared with zero in USLNG_Panama0. The increased LNG supply from the U.S. displaces that from other exporters to the Japan/S. Korea node (Table 10). Under the USLNG_Panama100 scenario as compared to the Base Case, Qatar and Australia experience decreases of approximately 46% (from 47 Bcm to 25 Bcm) and 4% (from 95 Bcm to 80 Bcm), respectively, in their LNG exports to Japan/S. Korea. In contrast, Qatar increases their LNG exports to Chinese markets from 26.9 Bcm to 49.6 Bcm under the USLNG_Panama100 scenario and from 26.9 to 61.8 Bcm under USLNG_200 scenario. Likewise, Australia exports LNG to China a lot more after its market shares are displaced by the Gulf of Mexico LNG from the U.S. The explanation is that as LNG exports are displaced in one market, suppliers will attempt to increase sales in other markets to maintain their profit. Overall, U.S. LNG causes a significant reduction in the total export volume of Asian LNG exporters to the Japanese/S. Korean market.

Figure 8 shows the changes in import sources for selected Asian countries. Under the USLNG_Panama0 scenario, without the presence of the Panama Canal expanded capacity even the model allows exports from Gulf of Mexico, LNG imports to Asia do not change. However, when the Panama Canal route is open, the total LNG imports to Asia increase for different reasons; Japan/S. Korea receives LNG directly from Gulf of Mexico exporters, the United States, and Trinidad & Tobago while China/Southeast Asia and India import

Table 10: Selected LNG flows from major LNG exporters in 2035 (Bcm)

Exporters	To Japan/S. Korea				To other Asia (China/S.E. Asia and India)				To Europe			
	Base	USLNG		USLNG Panama200	Base	USLNG		USLNG Panama200	Base	USLNG		USLNG Panama200
		Panama0	Panama100			Panama0	Panama100			Panama0	Panama100	
Australia	96.2	95.1	91.4	80	0	0	1.7	10.4	0	0	0	0
Qatar	47.8	47	25	13	26.9	27.9	49.6	61.8	24.9	24.9	24.9	24.9
Russia	8.3	8.3	8.3	8.3	0	0	0	0	12.2	0.8	10.2	12.6
USA	0	0	31.5	51.8	4.6	4.6	4.6	4.6	0	37.6	10.9	0
Trinidad	0	0	0	5.4	0	0	0	0	3	3	3	3
Algeria	0	0	0	0	0	0	0	0	68.4	62.3	62	66.4
Indonesia	0	0	0	0	3.6	3.6	3.6	3.6	0	0	0	0
Nigeria	1.8	4	0	0	35.8	35.1	24.6	24.6	5	3.9	12	10.7
Yemen	3	3	3	3	28.5	28.5	26.5	21.1	0	0	0	0

more LNG from Qatar and Australia. Lastly, imports by pipelines for China/Southeast Asia decrease due to the presence of more LNG supplied to the markets, see Figure 8.

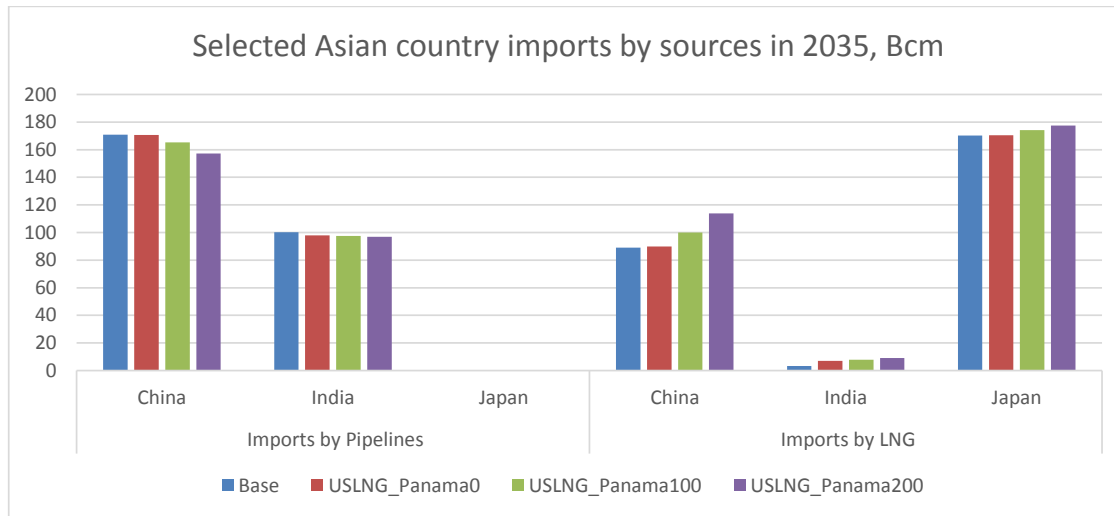


Figure 8: Selected Asian country imports by sources in 2035 Bcm

6 Conclusions

The aim of this study is to identify the influence of Panama Canal capacity level on LNG shipping and the LNG exports from the Gulf of Mexico under five different scenarios. The main conclusions can be summarized as follows:

- The model results show that without the Panama Canal expanded capacity, it is unprofitable to ship LNG from the Gulf of Mexico to Japan/S. Korea and U.S. LNG exports are shown to flow to Europe. However, the availability of the expanded Panama Canal allows for trade between the two basins and also reroutes approximately half of the total U.S. LNG exports from Europe to Asia, depending on the Canal capacity level. The main users of the Panama Canal route are the U.S. and Trinidad & Tobago.
- The Panama Canal capacity plays a significant role for the direction of the LNG exports from the Gulf of Mexico. When the capacity is limited, the U.S. becomes a swing gas exporter supplying both Asian and European gas markets. In addition, although the model allows large capacity for Panama Canal, the maximum gas flows through the Canal is only approximately 60 Bcm per year.
- More Panama Canal capacity (e.g., 100 vs. 200 ships/year) means more LNG trade but translates only to a greater number of small tankers.
- There is no doubt that Asian consumers will benefit from inexpensive gas through Panama Canal. LNG exports from the Gulf of Mexico increase competitiveness in Asian gas markets. The regional price disparity is shown to decrease over time. Japanese prices are improved about \$1/MMBtu in 2035 when enough capacity of Panama Canal provided.
- The presence of Gulf of Mexico-based LNG in the Japanese market significantly decreases the market shares of the existing exporters e.g., Qatar and Australia, who dynamically increase their sales to neighboring countries such as China and countries in Southeast Asia to compensate for the losses due to U.S. LNG exports. LNG from other Atlantic producers, such as Nigeria and Trinidad & Tobago, also uses the Panama Canal route.

APPENDIX

A Mathematical Formulation

Table A1: Notation used in the model

Sets	$a \in A$	Gas transportation arcs
	$d \in D$	Demand seasons e.g., { low, high}
	$p \in P$	Producers
	$m \in M$	Years
	$n \in N$	Model nodes
	$s \in S$	Storage facilities
	$t \in T$	Traders
	$a^+(n)$	Inward arcs
	$a^-(n)$	Outward arcs
	$l \in L$	Liquefiers
	$r \in R$	Regasifiers
	$j \in J$	LNG shipping route, e.g., {route without canal, Panama, Suez}
	$c \in C$	LNG carriers, e.g., {small, large, extra Large}
Variables	$SALES_{adm}^A$	Pipeline capacity assigned to a trader (mcm/d)
	$SALES_{pdm}^P$	Quantity sold by a producer to traders and liquefiers (mcm/d)
	$SALES_{sdm}^{SI}$	Storage injection capacity assigned for use by traders (mcm/d)
	$SALES_{sdm}^{SX}$	Storage extraction capacity assigned for use by traders (mcm/d)
	$SALES_{tndm}^T$	Quantity sold to end-user markets by traders (mcm/d)
	$SALES_{rdm}^{R \rightarrow T}$	Quantity sold to traders by regasifiers (mcm/d)
	$SALES_{dm}^{canal \rightarrow B}$	Canal capacity assigned for use by LNG transporters (mcm/d)
	$SALES_{ldm}^L$	Quantity sold to regasifiers by a liquefier (mcm/d)
	$SALES_{crljdm}^B$	LNG transported from liquefier l to node r via route j by LNG shipper c (mcm/d)
	$PURCH_{tndm}^T$	Quantity bought from a producer by a trader (mcm/d)
	$PURCH_{ldm}^{L \leftarrow P}$	Quantity bought from a producer by a liquefier (mcm/d)
	$PURCH_{ldm}^{T \leftarrow R}$	Quantity bought from a regasifier by a trader (mcm/d)
	$FLOW_{tadm}^T$	Arc flow by a trader (mcm/d)
	$LFLOW_{rljdm}^B$	LNG transported from node l to node r via route j (mcm/d)
	INJ_{tndm}^T	Quantity injected into storage by a trader (mcm/d)
	XTR_{tndm}^T	Quantity extracted from storage by a trader (mcm/d)
	Δ_{am}^A	Arc capacity expansion (mcm/d)
	Δ_{snm}^{SI}	Storage injection capacity expansion (mcm/d)
	Δ_{snm}^{SX}	Storage extraction capacity expansion (mcm/d)
	Δ_{snm}^{SW}	Storage working gas capacity expansion (mcm/d)
	Δ_{rm}^R	Regasification capacity expansion (mcm/d)
	Δ_{lm}^L	Liquefaction capacity expansion (mcm/d)
	Δ_{pm}^P	Production capacity expansion (mcm/d)
Δ_{cm}^B	LNG transportation capacity expansion (mcm/d)	

Dual variables	$\alpha, \beta \geq 0$	Dual variables of capacity restrictions
	φ free	Dual variables of mass balance constraints
	$\rho \geq 0$	Dual variables of capacity expansion limitations
	π free	Dual variables of market-clearing conditions for sold and bought quantities
	τ free	Dual variables of market-clearing conditions for capacity assignment and usage
	τ_{rljdm}^B	Dual variable of LNG transportation cost
Parameters	b_{am}^A	Arc capacity expansion costs (k\$/mcm)
	b_{sm}^{SI}	Storage injection capacity expansion costs (k\$/mcm)
	b_{sm}^{SX}	Storage extraction capacity expansion costs (k\$/mcm)
	b_{sm}^{SW}	Storage working gas capacity expansion costs (k\$/mcm)
	b_{cm}^B	LNG shipping capacity expansion costs (k\$/mcm)
	b_{pm}^P	Production capacity expansion costs (k\$/mcm)
	b_{lm}^L	Liquefaction capacity expansion costs (k\$/mcm)
	b_{rm}^R	Regasification capacity expansion costs (k\$/mcm)
	$c_{pm}^P(\cdot)$	Production costs (k\$/mcm)
	\overline{CAP}_{am}^A	Arc capacity (mcm/d)
	\overline{CAP}_{sm}^{SI}	Storage injection capacity (mcm/d)
	\overline{CAP}_{sm}^{SX}	Storage extraction capacity (mcm/d)
	\overline{CAP}_{cm}^B	LNG shipping capacity (mcm/d)
	\overline{CAP}_{lm}^L	Liquefaction capacity (mcm/d)
	\overline{CAP}_{lm}^R	Regasification capacity (mcm/d)
	\overline{CAP}_{jm}^{CJ}	Canal capacity (mcm/d)
	δ_{tn}^C	Level of market power exerted by a trader in a market $\delta_{tn}^C \in [0, 1]$
	$days_d$	Number of days in a season
	γ_m	Discount rate for a year, $\gamma_m \in (0, 1]$
	INT_{ndm}^W	Intercept of inverse demand curve (mcm/d)
	$loss_a$	Loss rate of gas in the transport arc, $l_a \in [0, 1]$
	$loss_s$	Loss rate of gas storage injection, $l_s \in [0, 1]$
	\overline{PR}_{pm}^P	Initial daily production capacity (mcm/d)
	\overline{PH}_p^P	Total producible reserves in the time horizon (mcm)
	SLP_{ndm}^W	Slope of the inverse demand curve (mcm/d/k\$)
	$\tau_{adm}^{A,reg}$	Regulated fee for arc usage (k\$/mcm)
	$\tau_{sdm}^{SI,reg}$	Regulated fee for storage injection (k\$/mcm)
	\overline{WG}_{sm}^S	Storage working gas capacity (mcm/d)
	$\overline{\Delta}_{am}^A$	Upper bound of arc capacity expansion (mcm/d)
	$\overline{\Delta}_{sm}^{SI}$	Upper bound of injection capacity expansion (mcm/d)
	$\overline{\Delta}_{sm}^{SX}$	Upper bound of extraction capacity expansion (mcm/d)
	$\overline{\Delta}_{sm}^{SW}$	Upper bound of working gas capacity expansion (mcm)
	$\overline{\Delta}_{cm}^B$	Upper bound of LNG shipping capacity expansion (mcm)
	$\overline{\Delta}_{pm}^P$	Upper bound of production capacity expansion (mcm)
	$\overline{\Delta}_{lm}^L$	Upper bound of liquefaction capacity expansion costs (mcm)
	$\overline{\Delta}_{rm}^R$	Upper bound of regasification capacity expansion costs(mcm)
	CC_m	CO ₂ cost (\$/ton of CO ₂ e)
	CE_{player}	CO ₂ emissions factor (0.1)
	$Dist_{rlj}$	Distance from r to l via route j in units of 1,000 nautical miles
	$MaxDist$	Maximum distance for tanker c that can travel in 1 day

α_{pm}^{cost}	Linear term in production cost function
β_{pm}^{cost}	Quadratic cost term in production cost function
γ_{pm}^{cost}	Logarithmic production cost function
$CanalDist$	Distance from start to end of Panama Canal
$AllowSpeed$	Maximum speed permitted on Panama Canal route
$Dayhr$	Number of day-light hours
$CAP^{P-canal}$	Panama Canal Capacity after converted to mcm/d
$CAP^{S-canal}$	Suez Canal Capacity after converted to mcm/d

Producer problem

A natural gas producer $p \in P$ is modeled as profit maximization. The daily profit is determined by the difference between the revenue, $\pi_{n(p)dm}^P SALES_{pdm}^P$, and the total costs, which are composed of the production cost $C_{pm}^P(SALES_{pdm}^P)$, the emission cost¹² $CC_{pm}^{ton} SALES_{pdm}^P \cdot CE_p^P$, and the capacity expansion cost, $b_{pm}^p \Delta_{pm}^p$ which are new features for producers in WGM 2014. The production cost function $C_{pm}^P(SALES_{pdm}^P)$ is a logarithmic function (see equation (A7)) of the involved capacity of capacity utilization. The annual profit is calculated by the sales rate multiplied by the number of day $days_d$ for each season with the discount rate γ_m for that particular year. The producer supplies gas to traders and liquefiers.

$$\max_{\substack{SALES_{pdm}^P \\ \Delta_{pm}^p}} \sum_{m \in M} \gamma_m \left\{ \sum_{d \in days} days_d \begin{bmatrix} \pi_{n(p)dm}^P SALES_{pdm}^P \\ -C_{pm}^P(SALES_{pdm}^P) \\ -CC_{pm}^{ton} SALES_{pdm}^P \cdot CE_p^P \end{bmatrix} - b_{pm}^p \Delta_{pm}^p \right\} \quad (A1)$$

The daily sales rates are restricted by the maximum initial capacity PR_p^P and the expansion in the previous years $\sum_{m' < m} \Delta_{pm}^p$.

$$\text{s.t. } SALES_{pdm}^P \leq \overline{PR}_{pm}^P + \sum_{m' < m} \Delta_{pm}^p \quad \forall d, m(\alpha_{pdm}^P) \quad (A2)$$

The total sales over the time horizon are limited by the reserves.

$$\sum_{m \in M} \sum_{d \in D} days_d SALES_{pdm}^P \leq \overline{PH}_p^P \quad \forall m(\beta_p^{PH}) \quad (A3)$$

The production capacity expansion is less than the budgetary constraints.

$$\Delta_{pm}^p \leq \overline{\Delta}_{pm}^p \quad \forall m(\rho_{pm}^P) \quad (A4)$$

The sales rate and the capacity expansion must not be negative.

$$SALES_{pdm}^P \leq 0 \quad \forall d, m \quad (A5)$$

$$\Delta_{pm}^p \leq 0 \quad \forall m \quad (A6)$$

The production cost function follows the fossil fuel supply cost proposed by Golombek et al. (1995), but we consider the expansion from the previous year. Details of the expansion of a logarithmic production cost function can be found in Huppmann (2013).

¹²In this study the emissions cost is zero.

$$C_{pm}^P (SALES_{pdm}^P) = (\alpha_{pm}^{cost} + \gamma_{pm}^{cost}) SALES_{pdm}^P + \beta_{pm}^{cost} SALES_{pdm}^2 + \gamma_{pm}^{cost} \left(\overline{PR_{pm}^P} + \sum_{m' < m} \Delta_{pm}^p - SALES_{pdm}^P \right) \ln \left(1 - \left(\frac{SALES_{pd}^P}{\overline{PR_{pm}^P} + \sum_{m' < m} \Delta_{pm}^p} \right) \right) \quad (A7)$$

Trader problem

Equation (A8) is the objective function for the trader and optimizes gas sales levels $SALES_{tndm}^T$, purchases of gas $PURCH_{tndm}^{T \leftarrow P}$ from producers and regasifiers. In addition, we assume the trader decides how much to inject INJ_{tndm}^T and XTR_{tndm}^T from storage. The trader maximizes the discounted profits, which come from the revenue $(\delta_{tn}^C \Pi_{ndm}^W(\cdot) + (1 - \delta_{tn}^C) \pi_{ndm}^W) SALES_{tndm}^T$ and the purchasing costs $\pi_{ndm}^P PURCH_{tndm}^{T \leftarrow P}$ and $\pi_{ndm}^R PURCH_{tndm}^{T \leftarrow R}$, the cost of using storage, $(\tau_{sndm}^{SI, reg} + \tau_{sndm}^{SI}) INJ_{tndm}^T + \tau_{sndm}^{SX} XTR_{tndm}^T$, and the emission cost¹³ $(CC_{tm}^{ton} SALES_{tndm}^T \cdot CE_T^T)$. In addition, the trader is responsible for the transportation costs, $(\tau_{adm}^{A, reg} + \tau_{adm}^A) FLOW_{tadm}^T$, for the gas. The traders are modeled as a weighted combination of strategic/competitive players depending on the market power parameter $\delta_{tn}^C \in [0, 1]$, where 0 represents competitive behavior and 1 indicates oligopolistic behavior with a knowledge of demand in the market.

$$\max \begin{matrix} SALES_{tndm}^T \\ PURCH_{tndm}^{T \leftarrow P} \\ PURCH_{tndm}^{T \leftarrow R} \\ FLOW_{tadm}^T \\ INJ_{tndm}^T \\ XTR_{tndm}^T \end{matrix} \sum_{m \in M} \gamma_m \sum_{d \in D} days_d \left\{ \sum_{n \in N(t)} \left[\begin{matrix} (\delta_{tn}^C \Pi_{ndm}^W(\cdot) + (1 - \delta_{tn}^C) \pi_{ndm}^W) SALES_{tndm}^T \\ - \pi_{ndm}^P PURCH_{tndm}^{T \leftarrow P} \\ - \pi_{ndm}^R PURCH_{tndm}^{T \leftarrow R} \\ - (CC_{tm}^{ton} SALES_{tndm}^T \cdot CE_T^T) \\ - \sum_{s \in S(t)} \left(\begin{matrix} (\tau_{sndm}^{SI, reg} + \tau_{sndm}^{SI}) INJ_{tndm}^T \\ + \tau_{sndm}^{SX} XTR_{tndm}^T \end{matrix} \right) \\ - \left(\sum_{a \in A(t)} (\tau_{adm}^{A, reg} + \tau_{adm}^A) FLOW_{tadm}^T \right) \end{matrix} \right] \right\} \quad (A8)$$

This constraint ensures the mass balance of sales, purchases, flows, and storage.

$$PURCH_{tndm}^{T \leftarrow R} + PURCH_{tndm}^T + \sum_{a \in a^+(n)} (1 - loss_a) FLOW_{tadm}^T + XTR_{tndm}^T = SALES_{tndm}^T + \sum_{a \in a} -FLOW_{tadm}^T + INJ_{tndm}^T \quad \forall n, d, m (\varphi_{tndm}^T) \quad (A9)$$

In each yearly storage cycle, the total extracted volumes must equal the loss-corrected injection volumes.

$$(1 - loss_s) \sum_{d \in D} days_d INJ_{tndm}^T = \sum_{d \in D} days_d XTR_{tndm}^T \quad \forall n, s \in S(N(t)), d, m (\varphi_{tndm}^S) \quad (A10)$$

All of the variables must be nonnegative.

$$SALES_{tndm}^T \geq 0 \quad \forall n, d, m \quad (A11)$$

$$PURCH_{tndm}^T \geq 0 \quad \forall n, d, m \quad (A12)$$

$$FLOW_{tadm}^T \geq 0 \quad \forall a, d, m \quad (A13)$$

¹³In this study the emissions cost is zero.

$$INJ_{tndm}^T \geq 0 \quad \forall n, d, m \quad (\text{A14})$$

$$XTR_{tndm}^T \geq 0 \quad \forall n, d, m \quad (\text{A15})$$

Liquefier problem

Liquefiers buy gas from the producers and sell it to regasifiers globally. The liquefier maximizes the discounted profit $\pi_{n(l)dm}^L SALES_{ldm}^L$ minus the purchasing costs, $\pi_{n(l)dm}^P PURCH_{ldm}^{L \leftarrow P}$, liquefaction costs $C_{lm}^L(SALES_{ldm}^L)$, and capacity investment costs $b_{lm}^L \Delta_{lm}^L$.

$$\max_{\substack{SALES_{ldm}^L \\ PURCH_{ldm}^{L \leftarrow P} \\ \Delta_{lm}^L}} \sum_{m \in M} \gamma_m \left\{ \sum_{d \in D} day_d \left[\begin{array}{l} \pi_{n(l)dm}^L SALES_{ldm}^L \\ -\pi_{n(l)dm}^P PURCH_{ldm}^{L \leftarrow P} \\ -C_{lm}^L(SALES_{ldm}^L) \end{array} \right] - b_{lm}^L \Delta_{lm}^L \right\} \quad (\text{A16})$$

The sales are restricted by the initial capacity CAP_l^L plus the total expansion $\sum_{m' < m} \Delta_{lm'}^L$, from the previous period.

$$SALES_{ldm}^L \leq CAP_l^L + \sum_{m' < m} \Delta_{lm'}^L \quad \forall d, m(\alpha_{ldm}^L) \quad (\text{A17})$$

The sales rates are also restricted by losses from the liquefaction process.

$$(1 - loss_l) PURCH_{ldm}^{L \leftarrow P} - SALES_{ldm}^L \geq 0 \quad \forall d, m(\phi_{ldm}^L) \quad (\text{A18})$$

The expansion in each time period is limited by budget restrictions.

$$\Delta_{lm}^L \leq \bar{\Delta}_{lm}^L \quad \forall m(\rho_{lm}^L) \quad (\text{A19})$$

All of the variables must be nonnegative.

$$SALES_{ldm}^L \geq 0 \quad (\text{A20})$$

$$PURCH_{ldm}^{L \leftarrow P} \geq 0 \quad (\text{A21})$$

$$\Delta_{lm}^L \geq 0 \quad (\text{A22})$$

LNG shipping operators

LNG transporters provide maritime transportation capacity to ship gas from a liquefier l to a regasifier r . Each transporter $c \in C$ owns ships of different sizes and operates at different shipping costs depending on the distances and tanker types. The capacity of each transporter is the aggregated capacity of all of the LNG carriers of a particular size that are available in the shipping market. The LNG transporter maximizes the discounted profit $\sum_{r,l} \tau_{rljdm}^B SALES_{crljdm}^B$ minus the shipping cost $C_{cm}^B(SALES_{crljdm}^B)$ and the costs of using the canal $\tau_{dm}^{P,toll}$ for Panama Canal and $\tau_{dm}^{S,toll}$ Suez Canal plus congestion fees $\tau_{dm}^{P,con}$ and $\tau_{dm}^{S,con}$ for LNG flows on route $j \in \{Panama, Suez\}$. The endogenous investment for LNG tanker $b_{cm}^B \Delta_{cm}^B$ is also considered if it is profitable in the future time period.

$$\begin{aligned}
& \max_{\Delta_{cm}^B} SALES_{crljdm}^B \\
& \sum_{m \in M} \gamma_m \left\{ \sum_{d \in D} day_d \left\{ \begin{array}{l} \sum_{r,l} \tau_{rljdm}^B SALES_{crljdm}^B \\ - C_{cm}^B (SALES_{crljdm}^B) \\ - \sum_{j \in \{p_{canal}\}} (\tau_{dm}^{P.toll} + \tau_{dm}^{P.con}) SALES_{crljdm}^B \\ - \sum_{j \in \{s_{canal}\}} (\tau_{dm}^{S.toll} + \tau_{dm}^{S.con}) SALES_{crljdm}^B \end{array} \right\} - b_{cm}^B \Delta_{cm}^B \right\} \quad (A23)
\end{aligned}$$

The sales rates on maritime shipping are constrained by the capacity of the LNG carrier, the average ship speed, and the maximum distance traveled in one day. This constraint has units of mcm/1,000 nautical miles. The total capacity is the initial capacity plus the expansion from the previous time periods $\sum_{m' < m} \Delta_{cm'}^B$. We also assume LNG tankers take the same route back and forth from origin to destination.

$$\sum_{r,l} 2 * (SALES_{crljdm}^B * Dist_{rlj}) \leq max_dis_c * (CAP_c^B + \sum_{m' < m} \Delta_{cm'}^B) \quad \forall d, m(\alpha_{cdm}^B) \quad (A24)$$

The expansion for each time period is constrained by budget restrictions.

$$\Delta_{cm}^B \leq \bar{\Delta}_{cm}^B \quad \forall m(\rho_{cm}^B) \quad (A25)$$

The sales of extra-large ships are restricted on the Panama and Suez Canal routes.

$$SALES_{c \in \{Exlarge\}rlj \in \{S_{canal}\}dm}^B = 0 \quad \forall r, l, d, m(\beta_{c \in \{c_{large}\}rljdm}^B) \quad (A26)$$

$$SALES_{c \in \{Exlarge\}lj \in \{P_{canal}\}dm}^B = 0 \quad \forall r, l, d, m(\beta_{c \in \{c_{large}\}rljdm}^B) \quad (A27)$$

All of the variables must be nonnegative.

$$SALES_{crljdm}^B \geq 0 \quad (A28)$$

$$\Delta_{cm}^B \geq 0 \quad (A29)$$

Regasifier problem

The regasifier maximizes the discounted profit from the sellers to the traders $SALES_{rdm}^{R \rightarrow T}$ minus the costs of purchases, $\sum_{rlj} \pi_{n(l)dm}^L LFLOW_{rljdm}^B$ the cost of shipping from the LNG transporter $\sum_{(r,l,j)} \{LFLOW_{rljdm}^B (\tau_{rljdm}^B)\}$, the cost of the regasification process $C_{rm}^R (SALES_{rdm}^{R \rightarrow T})$, and the capacity expansion cost $b_{rm}^R \Delta_{rm}^R$.

$$\begin{aligned}
& \max_{SALES_{rdm}^{R \rightarrow T}, SALES_{rdm}^{R \rightarrow M}, LFLOW_{rljdm}^B, \Delta_{rm}^R} \\
& \sum_{m \in M} \gamma_m \left\{ \sum_{d \in D} day_d \left[\begin{array}{l} \pi_{n(r)dm}^R SALES_{rdm}^{R \rightarrow T} \\ - \sum_{rlj} \pi_{n(l)dm}^L LFLOW_{rljdm}^B \\ - \sum_{(r,l,j)} \{LFLOW_{rljdm}^B (\tau_{rljdm}^B)\} \\ - C_{rm}^R (SALES_{rdm}^{R \rightarrow T}) \end{array} \right] - b_{rm}^R \Delta_{rm}^R \right\} \quad (A30)
\end{aligned}$$

The sales rates are constrained by the initial capacity plus the expansion from the previous time periods.

$$SALES_{rdm}^{R \rightarrow T} \leq CAP_r^R + \sum_{m' < m} \Delta_{rm'}^R \quad \forall d, m(\alpha_{rdm}^R) \quad (A31)$$

This constraint considers losses incurred in maritime transport and the regasification process.

$$\sum_{lrj} (1 - loss_{lrj}) * (1 - loss_r) * LFLOW_{rljdm}^B \geq SALES_{rdm}^{R \rightarrow T} \quad \forall d, m(\phi_{rdm}^R) \quad (A32)$$

The expansion for each time period is constrained by budget restrictions.

$$\Delta_{rm}^R \leq \bar{\Delta}_{rm}^R \quad \forall m(\rho_{rm}^R) \quad (A33)$$

The minimum purchases for long-term LNG contracts are enforced. Future contracts are assumed to have the same volume before their term expires.

$$\sum_j LFLOW_{rljdm}^B \geq Contract_{rldm}^R \quad \forall r, l, d, m(\varepsilon_{rldm}^R) \quad (A34)$$

All of the variables must be non-negative.

$$SALES_{rdm}^{R \rightarrow M} \geq 0 \quad (A35)$$

$$SALES_{rdm}^{R \rightarrow T} \geq 0 \quad (A36)$$

$$LFLOW_{rljdm}^B \geq 0 \quad (A37)$$

$$\Delta_{rm}^R \geq 0 \quad (A38)$$

Canal operator problem

The canal operator provides shorter distances to the LNG transporter compared to the regular route from the liquefier l to the regasifier r for an additional charge. The canal operator maximizes his discounted profit from the canal toll $\tau_{dm}^{P.toll}, \tau_{dm}^{S.toll}$ and congestion fees $\tau_{dm}^{P.con}, \tau_{dm}^{S.con}$ minus the operating costs C_{dm}^{PCanal} ($SALES_{dm}^{P.canal \rightarrow B}$) and C_{dm}^{SCanal} ($SALES_{dm}^{S.canal \rightarrow B}$).

$$\max_{\substack{SALES_{dm}^{P.canal \rightarrow B} \\ SALES_{dm}^{S.canal \rightarrow B}}} \sum_{m \in M} \gamma_m \left\{ \sum_{d \in D} \text{day}_d \left[\begin{array}{l} (\tau_{dm}^{P.toll} + \tau_{dm}^{P.con}) SALES_{dm}^{P.canal \rightarrow B} \\ (\tau_{dm}^{S.toll} + \tau_{dm}^{S.con}) SALES_{dm}^{S.canal \rightarrow B} \\ - C_{dm}^{PCanal} (SALES_{dm}^{P.canal \rightarrow B}) \\ - C_{dm}^{SCanal} (SALES_{dm}^{S.canal \rightarrow B}) \end{array} \right] \right\} \quad (A39)$$

The sales rates for the Panama Canal is restricted by speed allowance and daylight hours, see (A40).¹⁴ The left-hand side of this constraint shows how much gas flows in mcm per day through the Canal multiplied by the distance from the start of the Canal to the end of Canal (50 nautical miles). So the units of the left-hand side are mcm.nautical miles per day. For the right-hand side, the allowed average speed (8 nautical miles per hour) is multiplied by the number of operating hours per day (12 hours from sunrise to sunset) and the capacity in mcm per day, so we get the same units (mcm*nautical miles per day) as the left-hand side.

$$SALES_{dm}^{P.canal \rightarrow B} CanalDist \leq AllowSpeed * Dayhr * CAP^{P.canal} \quad \forall d, m(\alpha_{dm}^{P.Canal}) \quad (A40)$$

¹⁴The Panama Canal Authority requires the fleets to maintain a speed of 5 knots. However, the average speed is 8 knots.

The sales rates for the Suez canals are limited by its capacity.¹⁵

$$SALES_{dm}^{S_canal \rightarrow B} \leq CAP^{S_canal} \quad \forall d, m(\alpha_{dm}^{S_Canal}) \quad (A41)$$

All of the variables must be non-negative.

$$SALES_{dm}^{P_canal \rightarrow B} \geq 0 \quad (A42)$$

$$SALES_{dm}^{S_canal \rightarrow B} \geq 0 \quad (A43)$$

Transmission system operators

The transmission system operator (TSO) provides an economic mechanism to efficiently allocate international transport capacity to traders. The TSO maximizes the discounted profit that results from selling arc capacity to traders from $SALES_{adm}^A$ minus the investment costs for capacity expansions Δ_{am}^A and CO₂ costs $CC_{tsom}^{ton} SALES_{adm}^A \cdot CE_{tso}^{TSO}$.

$$\max_{\Delta_{am}^A} SALES_{adm}^A \sum_{m \in M} \gamma_m \left\{ \sum_{d \in D} days_d \left[-CC_{tsom}^{ton} SALES_{adm}^A \cdot CE_{tso}^{TSO} \right] - \sum_a b_{am}^A \Delta_{am}^A \right\} \quad (A44)$$

The assigned capacity is restricted by the available capacity. The available arc capacity at arc a is the sum of the initial arc capacity \overline{CAP}_{am}^A and the capacity expansions in the previous year $\sum_{m' < m} \Delta_{am'}^A$. The sales are limited by capacity and the expansion from the previous year.

$$SALES_{adm}^A \leq \overline{CAP}_{am}^A + \sum_{m' < m} \Delta_{am'}^A \quad \forall a, d, m(\alpha_{adm}^A) \quad (A45)$$

There may be budgetary or other limits on the yearly capacity expansions.

$$\Delta_{am}^A \leq \overline{\Delta}_{am}^A \quad \forall a, m(\rho_{am}^A) \quad (A46)$$

All of the variables must be non-negative.

$$SALES_{adm}^A \geq 0 \quad \forall m, d \quad (A47)$$

$$\Delta_{am}^A \geq 0 \quad \forall m \quad (A48)$$

Storage operator

The storage operator provides storage capacity to the traders. The revenue term is calculated by $\tau_{sdm}^{SI} SALES_{sdm}^{SI} + \tau_{sdm}^{SX} SALES_{sdm}^{SX}$ minus the expansion cost $b_{sm}^{SX} \Delta_{sm}^{SX} + b_{sm}^{SI} \Delta_{sm}^{SI} + b_{sm}^{SW} \Delta_{sm}^{SW}$ and the emission cost $CC_{sm}^{ton} \cdot (SALES_{pdm}^{SI} + SALES_{pdm}^{SX}) \cdot CE_s^S$.

$$\max_{\substack{SALES_{sdm}^{SX} \\ SALES_{sdm}^{SI} \\ \Delta_{sm}^{SX}, \Delta_{sm}^{SI}, \Delta_{sm}^{SW}}} \sum_{m \in M} \gamma_m \sum_{d \in D} days_d \left[\begin{array}{l} \tau_{sdm}^{SI} SALES_{sdm}^{SI} + \tau_{sdm}^{SX} SALES_{sdm}^{SX} \\ - (b_{sm}^{SX} \Delta_{sm}^{SX} + b_{sm}^{SI} \Delta_{sm}^{SI} + b_{sm}^{SW} \Delta_{sm}^{SW}) \\ - (CC_{sm}^{ton} \cdot (SALES_{pdm}^{SI} + SALES_{pdm}^{SX}) \cdot CE_s^S) \end{array} \right] \quad (A49)$$

¹⁵The Suez Canal can accommodate up to 106 vessels in one north-bound and two south-bound convoys. In addition Suez Canal operate at night so that the constraint is simpler than Panama Canal.

The aggregate injection rate in any season is restricted by the injection capacity (A50). Injection capacities can be expanded; therefore, the aggregate previous yearly expansions $\sum_{m' < m} \Delta_{sm'}^{SI}$ must be added to the initial capacity \overline{INJ}_s^S to determine the total capacity. Equation (A51) provides the limits on the extraction from storage, and condition (A52) represents the working gas limitations.

$$SALES_{sdm}^{SI} \leq \overline{CAP}_{sm}^{SI} + \sum_{m' < m} \Delta_{sm'}^{SI} \quad \forall m, d(\alpha_{sdm}^{SI}) \quad (\text{A50})$$

$$SALES_{sdm}^{SX} \leq \overline{CAP}_{sm}^{SX} + \sum_{m' < m} \Delta_{sm'}^{SX} \quad \forall m, d(\alpha_{sdm}^{SX}) \quad (\text{A51})$$

$$\sum_{d \in D} \text{days} SALES_{sdm}^{SX} \leq \overline{WG}_{sm}^S + \sum_{m' < m} \Delta_{sm'}^{SX} \quad \forall m(\alpha_{sm}^{SW}) \quad (\text{A52})$$

The limitations on the allowable capacity expansions are modeled as follows:

$$\Delta_{sm}^{SW} \leq \overline{\Delta}_{sm}^{SW}, \quad \forall m(\rho_m^{SW}) \quad (\text{A53})$$

$$\Delta_{sm}^{SI} \leq \overline{\Delta}_{sm}^{SI}, \quad \forall m(\rho_m^{SI}) \quad (\text{A54})$$

$$\Delta_{sm}^{SX} \leq \overline{\Delta}_{sm}^{SX}, \quad \forall m(\rho_m^{SX}) \quad (\text{A55})$$

All of the variables must be non-negative.

$$SALES_{sdm}^{SI} \geq 0, \quad \forall m, d \quad (\text{A56})$$

$$SALES_{sdm}^{SX} \geq 0, \quad \forall m, d \quad (\text{A57})$$

$$\Delta_{sm}^{SW} \geq 0, \quad \forall m \quad (\text{A58})$$

$$\Delta_{sm}^{SX} \geq 0, \quad \forall m \quad (\text{A59})$$

$$\Delta_{sm}^{SI} \geq 0, \quad \forall m \quad (\text{A60})$$

Market-clearing conditions

Market clearing conditions tie the producers to traders and liquefiers. The total sales from producers equals the purchases from traders and liquefiers.

$$SALES_{pdm}^P = \sum_{l \in L(p)} PURCH_{ldm}^{L \leftarrow P} + \sum_{t \in T(p)} PURCH_{tn(p)dm}^T, \quad \forall p, d, m(\pi_{n(p)dm}^P) \quad (\text{A61})$$

The injection capacity offered by a storage operator equals the total of injection from all traders. The market clearing condition injection capacity is

$$SALES_{sdm}^{SI} = \sum_{t \in T(N(s))} INJ_{tsdm}^T \quad \forall s, d, m(\tau_{sdm}^{SI}) \quad (\text{A62})$$

The extraction capacity offered by a storage operator equals the total of extraction from all traders. The market clearing condition extraction capacity is

$$SALES_{sdm}^{SX} = \sum_{t \in T(N(s))} XTR_{tsdm}^T \quad \forall s, d, m(\tau_{sdm}^{SX}) \quad (\text{A63})$$

The pipeline capacity offered by a pipeline operator equals the total of flows from all traders. The market clearing condition for arc capacity flow is

$$SALES_{adm}^A = \sum_t FLOW_{tadm}^T \quad \forall a, d, m(\tau_{adm}^A) \quad (A64)$$

The total sales from liquefiers equals the total flows from different routes to regasifier. The market clearing condition between the liquefiers and the regasifiers is

$$\sum_{l \in L(n(l))} SALES_{ldm}^L = \sum_{j \in J} \sum_{r \in R} LFLOW_{rljdm}^{R \leftarrow L} \quad \forall d, m(\pi_{n(l)dm}^L) \quad (A65)$$

The flow on the route j from liquefier l to regasifier j equals the total shipping capacity offered by different shipping operators. The market clearing condition between the regasifiers and the LNG transporters is

$$\sum_c SALES_{crljdm}^B = LFLOW_{rljdm}^B \quad \forall r, l, d, m(\tau_{rljdm}^B) \quad (A66)$$

The canal capacity offered by canal operator equals the total flows from all LNG shipping operators on the canal routes. The market-clearing conditions between the canal operators and the LNG transporters are:

$$SALES_{dm}^{P.canal \rightarrow B} = \sum_{c,r,l} SALES_{crljdm}^B \quad \forall j \in \{P\text{-Cannal}\}, d, m(\tau_{dm}^{P.canal \text{ toll}}) \quad (A67)$$

$$SALES_{dm}^{S.canal \rightarrow B} = \sum_{c,r,l} SALES_{crljdm}^B \quad \forall j \in \{S\text{-Cannal}\}, d, m(\tau_{dm}^{S.canal \text{ toll}}) \quad (A68)$$

Market-clearing conditions for final demand

$$\pi_{ndm}^W = INT_{ndm}^W - SLP_{ndm}^W \left(\sum_t SALES_{tndm}^T \right) \quad \forall m, d, m(\pi_{ndm}^W) \quad (A69)$$

B KKT conditions

KKT conditions for the producer problem

$$0 \leq days_d \left[\gamma_m \left(-\pi_{n(p)dm}^P + \frac{\partial c_{pm}^P(SALES_{pdm}^P)}{\partial SALES_{pdm}^P} + CC_{pm}^{ton} \cdot CE_p^p \right) \right] \\ + \alpha_{pdm}^P + days_d \beta_p^P \perp SALES_{pdm}^P \geq 0 \quad \forall d, m \quad (B1)$$

$$0 \leq \overline{PR}_{pm}^P + \sum_{m' < m} \Delta_{pm}^p - SALES_{pdm}^P \perp \alpha_{pdm}^P \geq 0 \quad \forall d, m \quad (B2)$$

$$0 \leq \overline{PH}_p^P - \sum_{m \in M} \sum_{d \in D} days_d SALES_{pdm}^P \perp \beta_p^P \geq 0 \quad (B3)$$

$$0 \leq \gamma_m b_{pm}^p + \sum_{m' > m} \frac{\partial c_{pm'}^P(\cdot)}{\partial \Delta_{pm}^p} - \sum_{m' > m} \sum_d \alpha_{pdm}^P + \rho_{pm}^P \perp \Delta_{pm}^p \geq 0 \quad \forall m \quad (B4)$$

$$0 \leq \overline{\Delta}_{pm}^P - \Delta_{pm}^P \perp \rho_{pm}^P \geq 0 \quad \forall m \quad (B5)$$

KKT conditions for the trader problem

$$0 \leq \text{days}_d \left[\gamma_m \left(- \left(\delta_{tn}^C SLP_{ndm}^M SALES_{tndm}^T \right) \right) \right. \\ \left. + \phi_{tndm}^T \perp SALES_{tndm}^T \geq 0, \quad \forall n, d, m \right] \quad (\text{B6})$$

$$0 \leq \text{days}_d [\gamma_m \pi_{ndm}^P] - \phi_{tndm}^T \perp PURCH_{tndm}^{T \leftarrow P} \geq 0 \quad \forall n \in N(p(t)), d, m \quad (\text{B7})$$

$$0 \geq \text{days}_d [\gamma_m \pi_{n(r)dm}^R] - \phi_{tndm}^T \perp PURCH_{tndm}^{T \leftarrow R} \geq 0 \quad \forall n \in N(r(t)), d, m \quad (\text{B8})$$

$$0 \geq \text{days}_d \gamma_m \left(\tau_{ndm}^{SI, reg} + \tau_{ndm}^{SI} \right) + \phi_{tndm}^T \\ - (1 - \text{loss}_n) \text{days}_d \phi_{tndm}^S \perp INJ_{tndm}^T \geq 0 \quad \forall n, m \quad (\text{B9})$$

$$0 \leq \text{days}_d \gamma_m \left(\tau_{ndm}^{SX} \right) - \phi_{tndm}^T + \text{days}_d \phi_{tndm}^S \perp XTR_{tndm}^T \geq 0 \quad \forall n, m \quad (\text{B10})$$

$$0 \leq \text{days}_d \gamma_m \left(\tau_{sndm}^{A, reg} + \tau_{sndm}^A \right) + \phi_{tndm}^T \\ - (1 - \text{loss}_a) \phi_{tndm}^T \perp FLOW_{tndm}^T \geq 0 \quad \forall a = (n_{a-}, n_{a+}), \forall d, m \quad (\text{B11})$$

$$0 = \left[PURCH_{tndm}^T + PURCH_{tndm}^{T \leftarrow R} + \sum_{a \in a^+(n)} (1 - \text{loss}_a) FLOW_{tadm}^T + XTR_{tndm}^T \right. \\ \left. - SALES_{tndm}^T - \sum_{a \in a^-(n)} FLOW_{tadm}^T - INJ_{tndm}^T \right], \\ \varphi_{tndm}^T, \text{ free}, \quad \forall n, d, m \quad (\text{B12})$$

$$0 = (1 - \text{loss}_s) \sum_{d \in D} \text{days}_d INJ_{tsdm}^T \\ - \sum_{d \in D} \text{days}_d XTR_{tsdm}^T, \varphi_{tsdm}^S, \text{ free} \quad \forall n, s \in S(N(t)), d, m \quad (\text{B13})$$

KKT conditions for the liquefier problem

$$0 \leq \text{day}_d \left[\gamma_m \left(-\pi_{n(l)dm}^L + \frac{\partial C_{lm}^L(SALES_{ldm}^L)}{\partial SALES_{ldm}^L} \right) \right] + \alpha_{ldm}^L + \phi_{ldm}^L \perp SALES_{ldm}^L \geq 0 \quad \forall d, m \quad (\text{B14})$$

$$0 \leq \text{day}_d \left[\gamma_m \left(\pi_{n(l)dm}^P \right) \right] - 1 - \text{loss}_l \phi_{ldm}^L \perp PURCH_{ldm}^{L \leftarrow P} \geq 0 \quad \forall d, m \quad (\text{B15})$$

$$0 \leq \gamma_m b_{lm}^L - \sum_d \sum_{m' > m} \alpha_{ldm}^L + \rho_{lm}^L \perp \Delta_{lm}^L \geq 0 \quad \forall m \quad (\text{B16})$$

$$0 \leq CAP_i^L + \sum_{m' < m} \Delta_{lm'}^L - SALES_{ldm}^L \perp \alpha_{ldm}^L \geq 0 \quad \forall d, m \quad (\text{B17})$$

$$0 \leq (1 - \text{loss}_l) PURCH_{ldm}^{L \leftarrow P} - SALES_{ldm}^L \perp \phi_{ldm}^L \geq 0 \quad \forall d, m \quad (\text{B18})$$

$$0 \leq \bar{\Delta}_{lm}^L - \Delta_{lm}^L \perp \rho_{lm}^L \geq 0 \quad \forall m \quad (\text{B19})$$

KKT conditions for the LNG shipper problem

$$0 \leq \text{day}_d \gamma_m \left(-\tau_{rljdm}^B + \frac{\partial C_{cm}^B(SALES_{crljdm}^B)}{\partial SALES_{crljdm}^B} + \left\{ \begin{array}{l} \tau_{jdm}^{P_{canal} \text{ toll}} \quad j \in \{P_{canal}\} \\ \tau_{jdm}^{S_{canal} \text{ toll}} \quad j \in \{S_{canal}\} \end{array} \right\} \right) \\ + 2 * Dist_{rlj} * \alpha_{cdm}^B \perp SALES_{crljdm}^B \geq 0 \quad \forall d, m \quad (\text{B20})$$

$$0 \leq \gamma_m b_m^B - \sum_d \sum_{m' > m} MaxDist_c * \alpha_{cdm}^B + \rho_{cbm}^B \perp \Delta_{crm}^R \geq 0 \quad \forall m \quad (B21)$$

$$0 \leq -\sum_{r,l,j} 2 * (SALES_{crljdm}^B * Dist_{rlj}) + MaxDist_c * \left(CAP_c^B + \sum_{m' < m} \Delta_{cm'}^B \right) \perp \alpha_{cdm}^B \geq 0 \quad \forall d, m \quad (B22)$$

$$0 \leq \bar{\Delta}_{cm}^B - \Delta_{cm}^B \perp \rho_m^B \geq 0 \quad \forall m \quad (B23)$$

KKT conditions for the regasifier problem

$$0 \leq day_d \gamma_m \left[\left(\begin{array}{c} -\pi_{n(r)dm}^T \\ + \frac{\partial C_{rm}^R(SALES_{rdm}^{R \rightarrow T})}{\partial SALES_{rdm}^{R \rightarrow T}} \end{array} \right) \right] + \alpha_{rdm}^R + \phi_{rdm}^R \perp SALES_{rdm}^{R \rightarrow T} \geq 0 \quad \forall d, m \quad (B24)$$

$$0 \leq day_d \gamma_m \left(\pi_{n(l)dm}^L + \tau_{rljdm}^B \right) - ((1 - loss_{lrj}) * (1 - loss_r)) \phi_{rdm}^R - \varepsilon_{rldm}^R \perp LFLOW_{rljdm}^B \geq 0 \quad \forall r, l, j, d, m \quad (B25)$$

$$0 \leq \gamma_m b_{rm}^R - \sum_{m' > m} \sum_{d \in D} \alpha_{rdm}^R + \rho_{rm}^R \perp \Delta_{rm}^R \geq 0 \quad \forall m \quad (B26)$$

$$0 \leq CAP_r^R + \sum_{m' < m} \Delta_{rm'}^R - (SALES_{rdm}^{R \rightarrow T}) \perp \alpha_{rdm}^R \geq 0 \quad \forall d, m \quad (B27)$$

$$0 \leq \bar{\Delta}_{rm}^R - \Delta_{rm}^R \perp \rho_{rm}^R \geq 0 \quad \forall m \quad (B28)$$

$$0 \leq \sum_{r,l,j} ((1 - loss_{lrj}) * (1 - loss_r) * LFLOW_{rljdm}^B) - SALES_{rdm}^{R \rightarrow T} \perp \phi_{rdm}^R \geq 0 \quad \forall d, m \quad (B29)$$

$$0 \leq \sum_j LFLOW_{rljdm}^B - Contract_{rlm}^R \perp \varepsilon_{rlm}^R \geq 0 \quad \forall r, l, d, m \quad (B30)$$

KKT conditions for the storage operator problem

$$0 \leq -days_d \gamma_m (\tau_{sdm}^{SI} + CC_{sm}^{ton} . CE_s^S) + \alpha_{sdm}^{SI} \perp SALES_{sdm}^{SI} \geq 0 \quad \forall d, m \quad (B31)$$

$$0 \leq -days_d \gamma_m (\tau_{sdm}^{SX} + CC_{sm}^{ton} . CE_s^S) + \alpha_{sdm}^{SX} + days_d \alpha_{sdm}^{SW} \perp SALES_{sdm}^{SX} \geq 0 \quad \forall d, m \quad (B32)$$

$$0 \leq \gamma_m b_{sm}^{SI} - \sum_{d \in D} \sum_{m' > m} \alpha_{sdm'}^{SI} + \rho_m^{SI} \perp \Delta_{sm'}^{SI} \geq 0 \quad \forall m \quad (B33)$$

$$0 \leq \gamma_m b_{sm}^{SX} - \sum_{d \in D} \sum_{m' > m} \alpha_{sdm'}^{SX} + \rho_m^{SX} \perp \Delta_{sm'}^{SX} \geq 0 \quad \forall m \quad (B34)$$

$$0 \leq \gamma_m b_{sm}^{SW} - \sum_{d \in D} \sum_{m' > m} \alpha_{sdm'}^{SW} + \rho_m^{SW} \perp \Delta_{sm'}^{SW} \geq 0 \quad \forall m \quad (B35)$$

$$0 \leq \overline{CAP}_{sm}^{SI} + \sum_{m < m'} \Delta_{sm'}^{SI} - SALES_{sdm}^{SI} \perp \alpha_{sdm}^{SI} \geq 0 \quad \forall m, d \quad (B36)$$

$$0 \leq \overline{CAP}_{sm}^{SX} + \sum_{m < m'} \Delta_{sm'}^{SX} - SALES_{sdm}^{SX} \perp \alpha_{sdm}^{SX} \geq 0 \quad \forall m, d \quad (B37)$$

$$0 \leq \overline{WG}_{sm}^S + \sum_{m < m'} \Delta_{sm'}^{SW} - days_d SALES_{sdm}^{SX} \perp \alpha_{sdm}^{SW} \geq 0 \quad \forall m \quad (B38)$$

$$0 \leq \bar{\Delta}_{sm}^{SW} - \Delta_{sm}^{SW} \perp \rho_m^{SW} \geq 0 \quad \forall m \quad (B39)$$

$$0 \leq \bar{\Delta}_{sm}^{SI} - \Delta_{sm}^{SI} \perp \rho_m^{SI} \geq 0 \quad \forall m \quad (B40)$$

$$0 \leq \bar{\Delta}_{sm}^{SX} - \Delta_{sm}^{SX} \perp \rho_m^{SX} \geq 0 \quad \forall m \quad (B41)$$

KKT conditions for canal operator

$$0 \leq \text{day}_d \gamma_m \left(-\tau_{dm}^{P_toll} - \tau_{dm}^{P_con} + \frac{\partial C_{jdm}^{P_canal}(SALES_{jdm}^{P_canal \rightarrow B})}{\partial SALES_{jdm}^{P_canal \rightarrow B}} \right) + \text{Dist}^{P_canal} \alpha_{jdm}^{P_canal} \perp SALES_{jdm}^{P_canal \rightarrow B} \geq 0 \quad \forall d, m, j \in \{P_canal\} \quad (\text{B42})$$

$$0 \leq \text{day}_d \gamma_m \left(-\tau_{dm}^{S_toll} - \tau_{dm}^{S_con} + \frac{\partial C_{jdm}^{S_canal}(SALES_{jdm}^{S_canal \rightarrow B})}{\partial SALES_{jdm}^{S_canal \rightarrow B}} \right) + \alpha_{jdm}^{S_canal} \perp SALES_{jdm}^{S_canal \rightarrow B} \geq 0 \quad \forall d, m, j \in \{S_canal\} \quad (\text{B43})$$

$$0 \leq \text{AllowSpeed} * \text{Dayhr} * \text{CAP}^{P_canal} - SALES_{dm}^{P_canal \rightarrow B} \text{CanalDist} \perp \alpha_{jdm}^{P_canal} \geq 0 \quad \forall d, m, j \in \{P_canal\} \quad (\text{B44})$$

$$0 \leq SALES_{jdm}^{S_canal \rightarrow B} - \text{CAP}^{S_canal} \perp \alpha_{jdm}^{S_canal} \geq 0 \quad \forall d, m, j \in \{S_canal\} \quad (\text{B45})$$

KKT conditions for the system operator problem

$$0 \leq \gamma_m \text{days}_d \left(-\tau_{adm}^A + CC_{tsom}^{ton} \cdot CE_{tso}^{TSO} \right) + \alpha_{adm}^A \perp SALES_{adm}^A \geq 0 \quad \forall a, d, m \quad (\text{B46})$$

$$0 \leq \gamma_m b_{am}^A - \sum_{d \in D} \sum_{m' > m} \alpha_{adm'}^A + \rho_m^A \perp \Delta_{adm}^A \geq 0 \quad \forall a, m \quad (\text{B47})$$

$$0 \leq \overline{\text{CAP}}_{am}^A + \sum_{m < m'} \Delta_{am'}^A - SALES_{adm}^A \perp \alpha_{adm}^A \geq 0 \quad \forall a, d, m \quad (\text{B48})$$

$$0 \leq \overline{\Delta}_{am}^A - \Delta_{am}^A \perp \rho_{am}^A \geq 0 \quad \forall m \quad (\text{B49})$$

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