FCN Working Paper No. 12/2017

Impacts of an Ice-Free Northeast Passage on LNG Trading: Transport Routes and Optimal Capacity Planning

Michael Schach and Reinhard Madlener

September 2017

Institute for Future Energy Consumer Needs and Behavior (FCN)

School of Business and Economics / E.ON ERC

FCN Working Paper No. 12/2017

Impacts of an Ice-Free Northeast Passage on LNG Trading: Transport Routes and Optimal Capacity Planning

September 2017

Authors´ addresses:

Michael Schach
RWTH Aachen University
Templergraben 55
52056 Aachen, Germany
E-Mail: Michael.Schach@rwth-aachen.de

Reinhard Madlener
Institute for Future Energy Consumer Needs and Behavior (FCN)
School of Business and Economics / E.ON Energy Research Center
RWTH Aachen University
Mathieustrasse 10
52074 Aachen, Germany
E-Mail: RMadlener@eonerc.rwth-aachen.de

Publisher: Prof. Dr. Reinhard Madlener
Chair of Energy Economics and Management
Director, Institute for Future Energy Consumer Needs and Behavior (FCN)
E.ON Energy Research Center (E.ON ERC)
RWTH Aachen University
Mathieustrasse 10, 52074 Aachen, Germany
Phone: +49 (0) 241-80 49820
Fax: +49 (0) 241-80 49829
Web: www.fcn.eonerc.rwth-aachen.de
E-mail: post_fcn@eonerc.rwth-aachen.de

Impacts of an Ice-Free Northeast Passage on LNG Trading: Transport Routes and Optimal Capacity Planning

Michael Schach[1] and Reinhard Madlener[2,*]

[1] *RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany*

[2] *Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics / E.ON Energy Research Center, RWTH Aachen University, Mathieustraße 10, 52074 Aachen, Germany*

September 2017

Abstract

We analyze the significance of an ice-free Northeast Passage (NEP) as a shipping route for LNG, and the impacts on alternative transport routes and -capacities. The following aspects are considered: (1) Trends in LNG production, particularly in the Russian Arctic; (2) Developments in the Asian LNG consumer market; (3) Specifics and prospects of Arctic shipping. The major LNG trade flows between producers and the Asian consumer market are modeled. Methods from Operations Research are contrasted and the Cycle-Cancelling Algorithm applied to the transportation problem, in order to achieve a cost-optimal capacity allocation. The impacts of demand variations and a chokepoint shutdown on transport routes and -capacities are considered. Concepts from competition theory are used to model the effects on LNG pricing. The key finding is that an ice-free NEP is highly relevant for shipping activities of Russian LNG producers. It constitutes a competitive advantage and notably impacts the supply competition and pricing on the Asian LNG market. A discussion of results and a conclusion critically reflect upon the research undertaken, providing an outlook and suggestions for future research.

Keywords: LNG, Northeast Passage, Arctic Shipping, Logistics, Cycle-Cancelling Algorithm;

---

[*] Corresponding author. Tel. +49 241 80 49 820, e-mail: RMadlener@eonerc.rwth-aachen.de (R. Madlener)

List of acronyms

AMSA	Arctic Marine Shipping Assessment	MOU	Memorandum of Understanding
AU	Australia	MY	Malaysia
CNPC	China National Petroleum Corporation	NE Asia	Northeast Asia
DV	Demand variation	NEP	Northeast Passage
EIA	U.S. Energy Information Administration	NSR	Northern Sea Route
FID	Final Investment Decision	PCR	Panama Canal Route
GECF	Gas Exporting Countries Forum	QT	Qatar
ID	Indonesia	RU	Russia
IEA	International Energy Agency	SAR	Search and Rescue
IGU	International Gas Union	SCR	Suez Canal Route
LNG	Liquefied Natural Gas	SOH	Strait of Hormuz
LTC	Long-term contract	TN	Transportation Network
METI	Ministry of Economy, Trade and Industry (of Japan)	US	United States of America

List of units

bn	billion	Mtoe	million tons of oil equivalent
Btu	British thermal unit	MTPA	million tons per annum
CO_2	carbon dioxide	NM	Nautical mile
M	million	t	ton
MMBtu	million British thermal units	$	U.S. dollar
MT	million tons		

1 Introduction

The sea routes connecting the Atlantic and the Pacific Ocean have been essential for European seafaring nations for centuries. When Christopher Columbus set sail for India in 1492 his ambition was to find a shorter way to Asia than the route around the Cape of Good Hope. The construction of the Suez Canal in the 19th century was a revolutionary milestone for Euro-Asian shipping. Until this day, the Suez Canal Route (SCR) remains crucial for navigation between Europe and Asia, with approximately 17,000 vessels traversing the passage annually (Suez Canal Authority, 2017a). However, there is a shorter maritime connection between European and Asian ports – the Northeast Passage (NEP) (Fig. 1). The history of Arctic shipping along the NEP began with its exploration by Adolf Nordenskiöld, a Swedish adventurer and explorer, in 1878/79. The extreme weather conditions, especially the extensive ice, forced Nordenskiöld to winter in the Russian Arctic before he was able to resume his journey in the summer of 1879 (Avango et al., 2014: 22). Yet, the global climate change and recession of the Arctic ice shield create new potential for the NEP as a substitute or seasonal supplement to the SCR (Fig. 1).

Maritime shipping is the most frequent form of transport for all kind of commodities. Marc Rich, the founding father of the global spot market for crude oil, facilitated the spread of the global shipping of hydrocarbons in the 1970s (Ammann, 2010: 34). However, the transportation of natural gas in the last decades took place using pipelines, due to both the physical particularities of the natural gas itself and the particularities of the trade contracts. The proportionally high volume of natural gas makes transportation with tankers only profitable if the gas is compressed, cooled, and liquefied. The capital-intensive construction of pipeline infrastructure facilitated the spread of static, bilateral, over-the-counter, long-term contracts (LTCs) between the major oil and gas companies or governments (Mokhatab et al., 2013: 39-41).

Nonetheless, decreasing costs for liquefaction due to technological progress, political and strategic calculations concerning supply diversification, and eminently the rising gas demand of Asian states like Japan or South Korea with no existing transnational pipeline infrastructure, foster the spread of liquefied natural gas (LNG). Generally, a global increase of energy demand by 30% and an increase of natural gas consumption by 50% until 2040 is forecasted by the International Energy Agency (IEA, 2016: 1). Although pipe-gas will presumably remain the most prevalent form of natural gas in the near-term future, LNG has the potential to occupy a substantial market niche in the light of changing market requirements. In 2015, the share of LNG in the global gas consumption accounted for only 10%, but has been spreading by an annual average of 6.6% since the beginning of the 21st Century, as indicated by the International Gas Union (IGU): more than half of the globally demanded LNG is consumed in three countries: Japan, South Korea, and China, making Asia the most influential region for the global LNG market (IGU, 2016: 10).

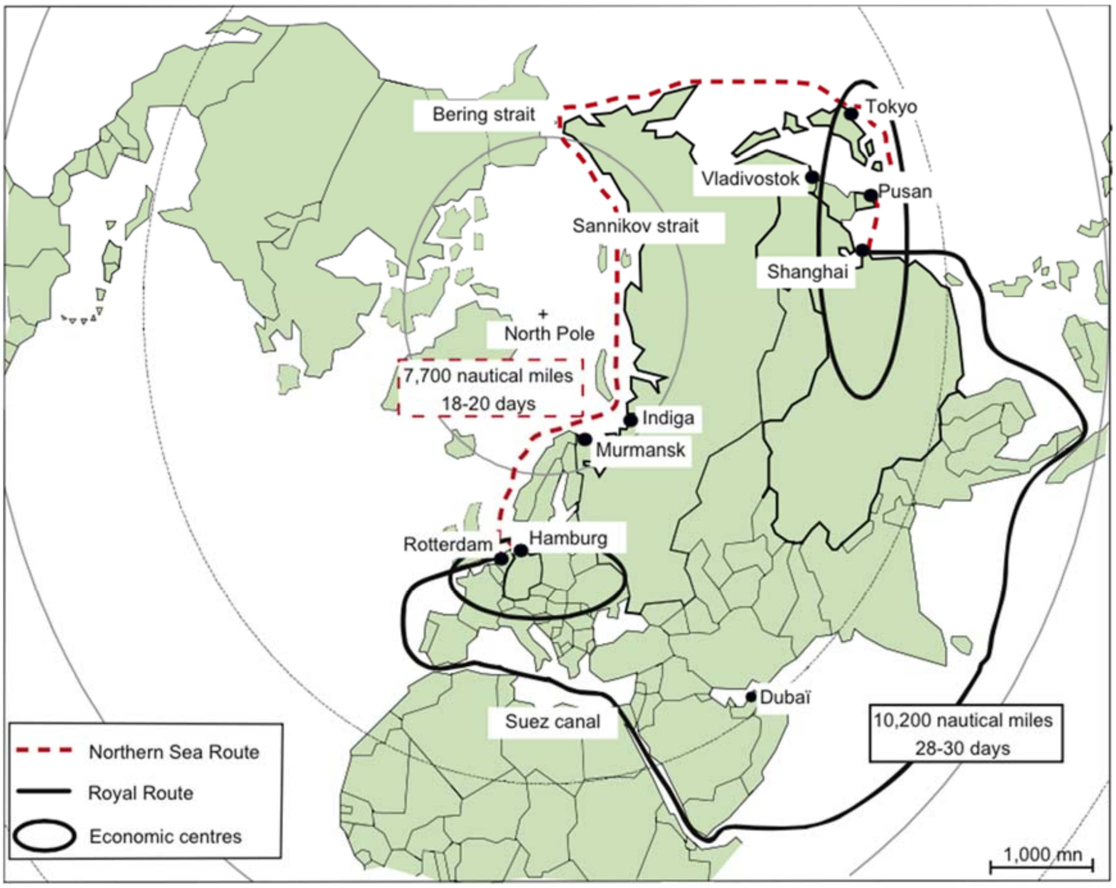

Fig. 1: The Northeast Passage / Northern Sea Route and the Suez Canal Route / Royal Route

Source: Verny and Grigentin (2009: 112)

An ice-free NEP would once more substantially change the major shipping routes between the Atlantic and the Pacific Ocean and impact all commercial shipping activities. In this paper, an exemplary analysis of the impacts on LNG shipping is undertaken. Over the last decades, the Russian Federation has been exporting its massive natural gas assets which are mainly located in Northwestern Siberia by pipelines. However, president Putin recently formulated the country's ambition, manifested by the construction of the Yamal LNG production site, to become the world's leading LNG exporter (Paraskova, 2017). Although this is a very ambitious statement from today's point of view, the seasonally ice-free NEP indeed rendered sea exports of Russian LNG possible. Given the fierce international LNG supply competition, the Arctic sea route and the thereby resulting cost and time savings can become an essential competitive advantage for Russian LNG producers.

This study aims at examining the significance and the impacts of the NEP on LNG shipping. First, the major developments in LNG supply and demand and with regard to the NEP are analyzed. Next, a hybrid algorithmic model is applied, considering these insights, to optimize the global LNG flows and capacities with regard to an ice-free NEP. In addition to the model, the effects on spatial price arbitrage are elaborated. The three research questions posted are: (1) What are the impacts of an ice-free Northeast Passage on LNG transport routes and transport capacities? (2) To which extent is an ice-free NEP a competitive advantage for Russian LNG producers? (3) How does the emergence of additional LNG capacities originating in Russia impact the pricing of LNG? To answer these questions, a short overview of the recent market developments is provided in section 2. In section 3, a geographical assessment of potential shipping activities along the NEP is undertaken. For the quantitative analysis in section 4, we make use of alternative network optimization algorithms from the field of Operations Research and concepts from competition theory, in order to model the impacts of an ice-free NEP on LNG flows and prices. Demand variation scenarios, a possible chokepoint shutdown, and the impacts on pricing are modeled in section 5. Finally, in section 6 a discussion of results and a conclusion provide a critical reflection of the research undertaken.

2 LNG supply and demand

The Fukushima nuclear disaster in Japan and increasing natural gas consumption in China resulted in an excessive demand for LNG in Asia between 2010 and 2014. These developments, in addition to high crude oil prices, led to a temporary price escalation for LNG (IGU, 2016: 15) that generated plenty of investments in various LNG upstream projects in the US, Australia, and other countries (Henderson, 2016a: 4). Most of these projects will come on stream until 2020, massively expanding the available LNG supply capacities. While in 2016 the global liquefaction capacity amounted to 301.5 MTPA, this number will increase by 46% to 453 MTPA in 2020. Specifically, the majority of this capacity derives from projects under construction in the US (62 MTPA) and Australia (53.8 MTPA) (IGU, 2016: 17,18). The abundance of supply will most probably be faced with a globally increased demand, leading to a further price integration.

The Russian Federation, whose primary export method for natural gas was the conventional pipeline, changed their supply strategy in 2013: In addition to Gazprom, the firm that obtained an export monopoly until then, the companies Rosneft and Novatek received export licenses for LNG (Motomura, 2014: 72). This liberalization provided the legal foundation for Novatek's Yamal LNG project that will boost the country's export capacities from currently 10 MTPA to 26.5 MTPA until 2020 (Novatek, 2017a; Table 1). The comparably low production costs of approximately $3-4/MMBtu (S&P Global Platts, 2016: 6; Henderson, 2016b: 24), numerous oil-indexed LTCs (Table 1), and the advantageous location on the shores of the NEP (Fig. 2), are factors that could ensure the project's competitiveness even under challenging market conditions. Novatek signed a Memorandum of Understanding (MOU) with partners from Japan and China concerning a follow-up project. The transport of hydrocarbons from the Russian Arctic produced at the Yamal site or any others, and executed by the fleet of ice-breaking tankers, will indicate whether the NEP has the potential to become a seasonal supplement or even substitute to the SCR for bulk shipping.

Table 1: LTCs of the Yamal LNG project

Purchaser	Volume (MTPA)	Duration (a)	Pricing (if known)	Destination (if known)
CNPC	3	20	Indexed to JCC	China
Total Gas & Power	3	24	-	-
Gazprom M&T Singapore	2.9	20	Crude oil index.	Asian-Pacific region
Gas Natural Fenosa	2.5	Long-term	-	Spain
Engie	1	23	-	-
Total Gas & Power	1	15	-	-
Shell International Trading Middle East	0.9	20	-	-
Gunvor	0.48	Long-term	-	-
Sum:	**14.78**	-	-	-

Source: Own compilation, based on Yamal LNG (2017a-d); Novatek (2017b-c); S&P Global Platts (2016): 6

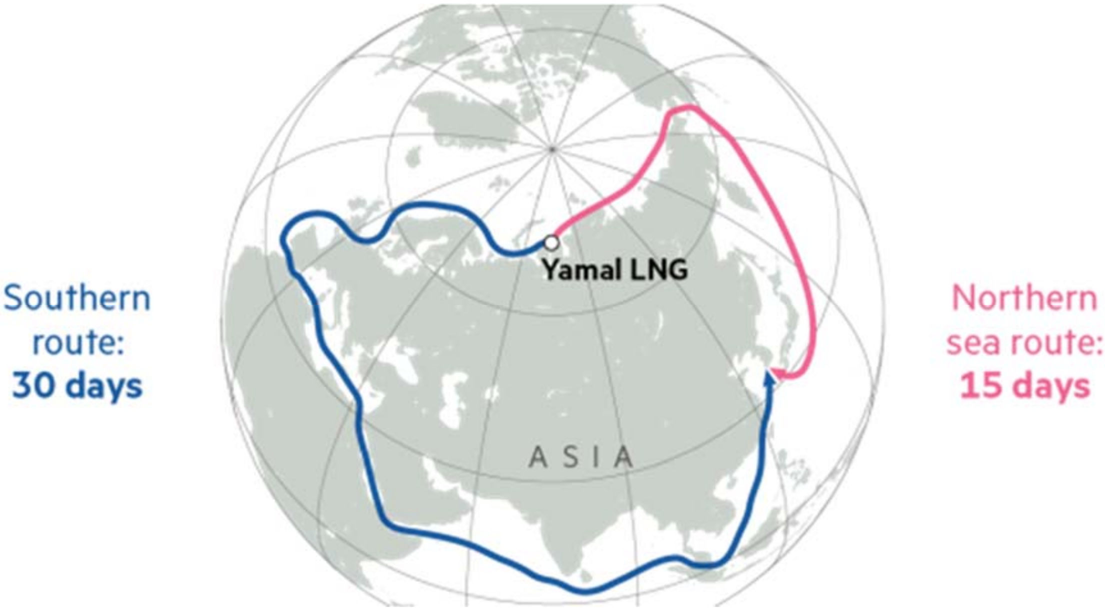

Fig. 2: Shipping scenarios of the Yamal LNG project

Source: Foy (2017)

The globally leading LNG consumers – Japan, South Korea, and China – heavily rely on natural gas in their future energy mix. While Japan and South Korea import their total demand with LNG carriers, approximately half of China's gas imports are transported through pipelines

(IGU, 2016: 10; METI, 2016b: 2; Kim et al., 2016: 202; Egging and Holz, 2016: 474). Therefore, the following major factors of influence in these Asian states will determine the future dissemination of natural gas and LNG:

(1) The degree of revival of Japan's nuclear power generation. The temporary but massive increase in Japan's LNG demand after the Fukushima fallout led to the high Asian premium prices in the first half of this decade (Table A1). The Japanese Ministry of Economy, Trade and Industry (METI) predicts a share of LNG amounting to 27% of Japan's energy mix by 2030 (METI, 2016c). In addition, the ministry has published very ambitious if not revolutionary objectives in their recent LNG strategy (Stern, 2016: 1). The strategy aims at creating an LNG trading hub in Japan and changing the market structure, fostering liquidity and flexibility. Expansion of tradability and spot trading, in addition to supply & demand-based pricing through a proper price discovery mechanism, as well as open and sufficient infrastructure, shall render the achievement of these goals possible (METI, 2016b: 5,7,8). However, a continuative phase-in of the nuclear power plants might challenge the importance of LNG in Japan's energy future.

(2) The significance of renewables in South Korea's future energy mix. Since nearly 96% of South Korea's primary energy sources are imported (Kim et al., 2016: 202), the country's energy diversification strategy foresees a massive expansion of renewables in the mid-term future (Yonhap News Agency, 2017). Nonetheless, LNG imports are expected to increase due to the enormous and fast-growing electricity demand. The South Korean government expects a power demand surplus of 64% by 2027 (Shim and Hong, 2016: 283). Moreover, further long-term ambitions concerning LNG are affirmed by various investments in upstream projects, infrastructure, and ice-breaking tankers (Moon et al., 2015: 18).

(3) The sustainability of China's environmental policy. The globally leading energy consumer (3098 Mtoe in 2015) and CO_2 emitter (9.5 bn t of CO_2 or 27.1% of the global carbon emissions in 2013) has introduced an environmental policy that foresees a cutback of coal-fired electricity generation (GECF, 2017: 15, 24, 31; Jiang, 2016: 866). If the policy is sustainably

executed, the share of coal as a source of power will decrease from some 75% today to 45% in 2040, whereas the general demand for electricity is anticipated to increase by 85% (IEA, 2016: 2,3). Indeed, a significant portion of this prospective demand could be substituted by natural gas.

According to the signed LTCs, the major part of the output of the Yamal LNG site are designated for Asian buyers. The past and future Chinese, Japanese, and South Korean investments in LNG production, particularly in the Arctic, underline the strategic importance of the Arctic as a future hydrocarbon hotspot and the NEP as an essential shipping route and a crucial element of the global LNG supply.

3 Shipping along the NEP

"The Northeast Passage (NEP) is defined as the set of sea routes from northwest Europe around North Cape (Norway) and along the north coast of Eurasia and Siberia through the Bering Strait to the Pacific" (Ellis and Brigham, 2009: 34). Retreating ice, significant hydrocarbon deposits and the ambitious infrastructure development plans of the Russian government indicate a promising future for the NEP as a globally relevant shipping route. Nevertheless, various constraints are to consider for an accurate assessment of the NEP's perspectives: political instability, unpredictable climatic conditions (weather, ice etc.), shallow waters, poor infrastructure, especially insufficient search and rescue (SAR) capabilities (Buixadé Farré et al., 2014: 299). Over and above, the specification of the freight is an element that must be considered. While commercial container shipping using a just-in-time system requires precise compliance with the delivery schedule; bulk cargo – hydrocarbons (oil, gas etc.) and minerals (nickel, copper, phosphates etc.) – does not necessitate on a just-in-time supply (Buixadé Farré et al., 2014: 302; Humpert and Raspotnik. 2012). The unforeseeable climatic conditions, especially the sudden emergence of ice, strongly impact the precisely scheduled trade flows, making the NEP rather ineligible for commercial cargo shipping. Therefore, the SCR will most probably remain a crucial route in the near- and mid-term future (Ragner, 2008: 116; Stephenson et al., 2013: 114). Notwithstanding, bulk freight, particularly those natural resources that are produced in the Arctic, can guarantee the relevance of the NEP for destinational shipping, with over 700 annual voyages in the period from 2020-2030 (Reeves et al., 2014: 382). Naturally, this forecast is directly correlated with prospective hydrocarbon production in the Arctic, facilitating the large-scale infrastructure development necessary for considerable, international shipping activities.

In contrast to shipping along the SCR, the Arctic climatic conditions, the ultra-sensitive marine environment and the Russian legislation require the usage of ice-reinforced vessels, massively limiting the number of shippers who have such tankers at their disposal, or are willing to pay for the costly ice-breaker escorts offered by Russian companies (Ellis and Brigham, 2009: 55; NSR Information office, 2017a). Thus, all meteorological forecasts anticipate an ice-free Arctic in the long-term future, making Arctic shipping activities inevitable (Buixadé Farré et al., 2014: 311; Kwok and Rothrock, 2009; Ellis and Brigham, 2009: 4). In the meantime, producers of Arctic natural resources along the NEP can benefit from this advantageous transport route for their products. In the following, the competitiveness of Arctic LNG exports to Asia and the impacts on the Asian markets are evaluated in some more detail. The evaluation is executed by the application of an algorithmic model adapted from Operations Research that allows us to study the prospects of ongoing and perspective LNG flows and volumes.

4 LNG transport routes and capacity optimization

4.1 Potentially suitable algorithms

In order to find the optimal solution for a transportation problem, various algorithms can be applied. However, before such an application a definition of ‘optimal’ is needed: What is the shortest or fastest way between multiple locations? Which bottlenecks have what impacts on the capacity planning? What is the most cost-effective route? In this section, several algorithms are introduced that are potentially useful to evaluate the relevance of the NEP for LNG shipping. Various scenarios provide an assessment of the competitiveness of different LNG producers. In addition, the impacts of a sudden shutdown of one of the depicted chokepoints, in the case of a terrorist attack, a natural catastrophe, or regarding the NEP an extensive freeze, are analyzed.

Bertsekas (1998) provides an extensive overview of algorithms that can be used in network optimization models. In general, a distinction can be made between Shortest Path Problems, Max-Flow Problems, and Min-Cost Flow Problems. The Label Setting algorithm invented by Dijkstra is the fundamental algorithm for shortest path problems. It will be examined hereafter in greater detail. There are various other approaches to solve shortest path problems, such as the Binary Heap Method, Dial's Algorithm, the Bellman-Ford Method, the D'Esopo-Pape Algorithm, the SLF and LLL Algorithms, and the Threshold Algorithm. Whereas the results of the different methods are of the same quality, the greatest distinction is the running time and efficiency of these alternative algorithms (Bertsekas, 1998: 65-81).

For the application envisaged in this paper, the fundamental Dijkstra Algorithm is sufficient. In a different context, when optimizing the routes between million nodes and edges, the running time might be of great significance, too. While there are multiple algorithms that can be applied to Shortest Path Problems, the Ford-Fulkerson Algorithm is the most eligible method to solve Max-Flow Problems. The algorithm is based on the Max-Flow/Min-Cut Theorem (Bertsekas, 1998: 121,125). The applicability of the algorithm is notably, because it also provides the foundation for the Cycle-Cancelling Algorithm to solve Min-Cost Flow Problems (Wayne, 2004: 4-17). In the following, the applicability of the interpretation of the LNG transport routes network as (1) a Shortest Path Problem, (2) a Max-Flow Problem, and (3) a Min-Cost Flow Problem is evaluated. To this end, the Dijkstra Algorithm, the Ford-Fulkerson Algorithm, and the Cycle-Cancelling Algorithm are used.

4.1.1 Dijkstra Algorithm (Shortest Path Problems)

In 1959, Dijkstra published an algorithm which determines the shortest distances of several nodes on a weighted, directed graph $G = (V,A)$ with a single source s in G, exclusively nonnegative edges in G, and a function $\omega(a): A \rightarrow \mathrm{R}^+$ (Dijkstra, 1959: 269, 270; Knuth, 1976: 1). A graph is weighted and directed if all edges are attributed with a certain value or weight and there is a flow direction from a source to a sink (Luebbecke, 2015: 6). The sea distances that are represented by the parameters, which are attributed to all edges of the graph, are ≥ 0. The various routes in the graph represent different paths from an origination to a destination and have a distinct flow direction. The length of the shortest path from s to v is denoted as $d(v)$.

1. In the initial stage, the attributed value at the source is $d(s) = 0$.
2. In the initial stage, the attributed value for every edge originating at s is $d(v) = \omega(s,v)$ and $p(v) = s$. All other edges, not originating as s, are attributed the value $d(v) = \infty$.
3. In the initial stage $S = \{s\}$.
4. In the first iteration, an unvisited node v is found, with the minimal distance $d(v)$ to s.
5. For every consequent iteration, the current value $d(u)$ and $n = d(v) + \omega(v,u)$ are compared. If $n < d(u)$, $d(u)$ is set $= n$ and $p(u)$ is set $= v$.
6. After each iteration, v is marked as visited and $S = \cup S\{v\}$.
7. If $S = V$, the algorithm terminates. If not, it proceeds with the iterations.

Note that, the algorithm applied in the present context has some caveats. The bottleneck capacity in this model is exclusively the distance. The corresponding costs and capacities, which are crucial in our application, cannot be integrated into this model. Moreover, the algorithm can only optimize the route between one single source and one single sink.

4.1.2 Ford-Fulkerson Algorithm (Max-Flow Problems)

The Ford-Fulkerson Algorithm, introduced by Ford and Fulkerson in 1956, determines the maximum flow through a network with capacity limitations (Ford and Fulkerson, 1956: 399). It solves Max-Flow Problems by iteratively increasing the value of the flow $f(u,v) = 0$ for all u,v in V.

1. At the beginning, the initial flow f is attributed with the value 0.

2. The flow value is increased by finding an augmenting path p (from source s to sink t) in the graph $G = (V,A)$.

3. The operation is repeated until there are no more augmenting paths left and the capacities along the edges are optimal. Finally, flow values already assigned to some edges may decrease for a greater total flow value (Cormen et al., 2009: 714, 715).

The Ford-Fulkerson Algorithm is the foundation for the Max-Flow/Min-Cut Theorem. According to the theorem, the value of max flows through the network equals the capacity of a min cut through the network (Wayne, 2004: 4-17). This insight is necessary for the application of the Cycle-Cancelling Algorithm. The extensive global LNG fleet of 410 tankers (approximately 500 expected by 2020) and the wide substitutability of the particular tankers make bottlenecks due to the unavailability of shipping vessels rather unlikely (IGU, 2016: 34). However, the limited availability of icebreakers, or icebreaking LNG tankers, may impact the maximal shipping capacities along the NEP. The Ford-Fulkerson algorithm, like Dijkstra's, is only able to optimize the capacities between one single source and a single sink. Therefore, we use yet another algorithm where possible capacity constraints are depicted as cost escalations.

4.1.3 Cycle-Cancelling Algorithm (Min-Cost Flow Problems)

Klein (1967) introduced a seminal method for the determination of minimal cost flows in assignment and transportation problems: The Cycle-Cancelling Algorithm (Klein, 1967: 205). Its objective is to identify, on a weighted and directed graph $G_f = (V,E_f)$, the routes with the least costs $l(u, v) = -l(v, u)$ attributed to an edge (u,v) *in* $E_f \setminus E$, for a commodity that is available at multiple sources s_n and shall be delivered to the model's sink t, in order to satisfy the attributed demand. Circulation f' *in* G_f is denoted with the function $f'\colon E_f \rightarrow \mathrm{R}_0^+$ (Ahuja et al., 1995: 27).

The optimization of LNG shipping routes through various chokepoints with costs as the primary bottleneck unit resembles a Min-Cost Flow Problem. An essential advantage of this model is the possibility to consider multiple sources and sinks. Most other optimization problems can be expressed as a Min-Cost Flow Problem, by the quantification of analogous bottleneck units as costs. The principle of the algorithm is both fundamental and efficient:

1. First, a max flow f in the network is determined, ignoring the costs. This can be done efficiently, by applying the previously introduced Max-Flow/Min-Cut Theorem. The Ford-Fulkerson Algorithm can be used to this end.

2. Next, negative cost-directed cycles K are identified in the network G_f and the flow along these cycles is augmented: $f = f + f'(K)$.

3. If $f'(K)$ is a circulation, the value of the flow does not increase when $f'(K)$ is added, because $w(f + f'(K)) = w(f) + w(f'(K)) = w(f) = W$.

4. At the same time, the costs do decrease because $l(f + f'(K)) = l(f) + l(f'(K)) < l(f)$, since $l(f'(K)) = f'(a) * \sum_{e \in K} l(e) < 0$ (with a being a random edge).

5. The algorithm terminates and the flows are cost-minimal when there are no negative cycles left (Nagy, 2003: 3).

4.2 Algorithmic transportation model

In order to model the relevant transportation problem and to apply the Cycle-Cancelling Algorithm to the graph, several assumptions have to be made and elements to be defined first.

4.2.1 Definition of the model's optimality criterion, sources and sink

We define the model as follows (I – XIV):

I: For the comparison of the competitiveness of different LNG producers, their production costs and the corresponding transportation costs are defined as the most crucial bottlenecks. The Cycle-Cancelling Algorithm provides an excellent solution for such an optimization problem.

II: All values, e.g. of the production and transportation costs, are approximations that vary in different sources. Predominantly, the model introduces the application of the Cycle-Cancelling Algorithm on LNG shipping routes, and evaluates the impacts of different scenarios, like a variation in the demand or the shutdown of a chokepoint.

III: The six prospective world's leading LNG exporters are defined by their projected production capacity in 2020, including the major sites currently under construction (Table 2).

IV: The three prospective world's leading LNG importers are defined by their current and predicted imports (Table 2).

Table 2: Leading LNG exporters and importers by 2020

Country	Exports in 2015 (MTPA)	Production capacity by 2020 (MTPA)	Imports in 2015 (MTPA)	Regasification capacity by 2020 (MTPA)
Qatar	77.8	147.2	-	-
Australia	29.4	86.6	-	-
US	0.3	63.45	-	-
Malaysia	25	30.2	-	-
Indonesia	16.1	27	-	-
Russia	10.9	26.1	-	-
Japan	-	-	85.6	192.7
South Korea	-	-	33.4	101.1
China	-	-	19.8	68.3

Source: Own compilation, based on IGU (2016: 7, 10, 61-69)

V: Volumes are depicted in tons and the corresponding costs in US Dollars.

VI: Due to the geographical proximity of the leading LNG consumers, and the estimated market integration that takes place in Japan and China (open access to regasification terminals, open access to domestic pipeline infrastructure, exceeding regasification capacities, trend against LTCs, gradual prevalence of spot trading etc.), the consumers are depicted as one integrated market (for details on the Asian LNG market integration see also Schach and Madlener, 2017).

VII: With the exceptions of Qatar and Indonesia, who have been artificially limiting their exports (EIA, 2017a), the states' total production capacities are assumed as their export capacities.

4.2.2 Capacities: Global LNG infrastructure and bottlenecks

VIII: Due to the massive active global LNG fleet and the vessels currently under construction (IGU, 2016: 69-85), whose capacity exceeds the produced volumes, unlimited capacities for the regular maritime shipping routes are assumed.

IX: The regasification capacities in Asia (Table A3) by far exceed the imports and the produced volumes of the exporting states. Thus, no bottlenecks in regasification capacities are assumed.

X: As previously described, the Russian legislation requires traversing vessels either to be ice-reinforced or to make use of the icebreaker assistance that is provided for a fee. The limited availability of both ice-reinforced tankers and icebreakers create a bottleneck. This bottleneck is assumed to limit the transport capacity to 30.1 MTPA.

4.2.3 LNG shipping routes and chokepoints

XI: The locations of different, national LNG plants are approximated to an average port location within the state's borders. Due to the assumption that the LNG is shipped to an integrated Asian market, all Japanese, South Korean and Chinese destinations are approximated to the location of Shanghai.

XII: It is assumed that there are no relevant chokepoints within the shipping routes of Australian, Indonesian, and Malaysian LNG producers (applicable to deliveries to Asia).

XIII: There are four relevant chokepoints (Northeast Passage, Panama Canal, Strait of Hormuz, Suez Canal) to be analyzed in the model. Hereafter, the acronyms NEP, PCR, SOH, and SCR are used for the corresponding routes. After the expansion of the Panama Canal and the Suez Canal, all chokepoints except for the NEP have overly sufficient capacities for the annually produced volumes of LNG (Canal de Panama, 2017a; Suez Canal Authority, 2017b; Kwok, 2012). Therefore, for the PCR, SCR, and SOH no capacity limits are assumed. Direct shipping routes with no chokepoints are no subject to a capacity limitation either.

5 Application of the algorithmic model

5.1 Scenarios considered and results

5.1.1 Scenarios

XIV: In Scenario 1, the demand in Asia perfectly matches all supply volumes that are on the market. In Scenario 2, demand variations (DV) are evaluated to compare the competitiveness of the suppliers. In Scenario 3, the shutdown of a certain chokepoint and the corresponding impacts are analyzed.

5.1.2 Procedural steps

Hereafter, the LNG routes and flows will be optimized in eight steps, using elements of the Ford-Fulkerson Algorithm and the Cycle-Cancelling Algorithm. Here is an overview of the subsequent steps:

Step 1: The producers, consumers, and all relevant routes are modeled. Production and transport costs are assigned to the edges.

Step 2: Ford-Fulkerson's Max-Flow/Min-Cut Theorem is applied in order to find the maximum flow through the network.

Step 3: The maximum flow is sent through the network.

Step 4: The 'take-back-capacities' in the network are detected.

Step 5: The network is examined for negative cost-directed cycles and, if any, the flow along this cycle is augmented.

Step 6: The flow along the negative cost-directed cycle is augmented until there are no more units to be reassigned.

Step 7: The algorithm terminates as soon as there are no negative cost-directed cycles left.

Step 8: The distribution of the produced and exported volumes along the routes is cost-optimal (cost-minimal).

5.1.3 Scenario 1: Route optimization – application

Step 1: On the left-hand side in Fig. 3, all production capacities of the states that are subject of the analysis are depicted. An artificial 'domestic' edge is incorporated into the model, in order to assign the production costs and possible export capacity limitations to the produced national volumes.

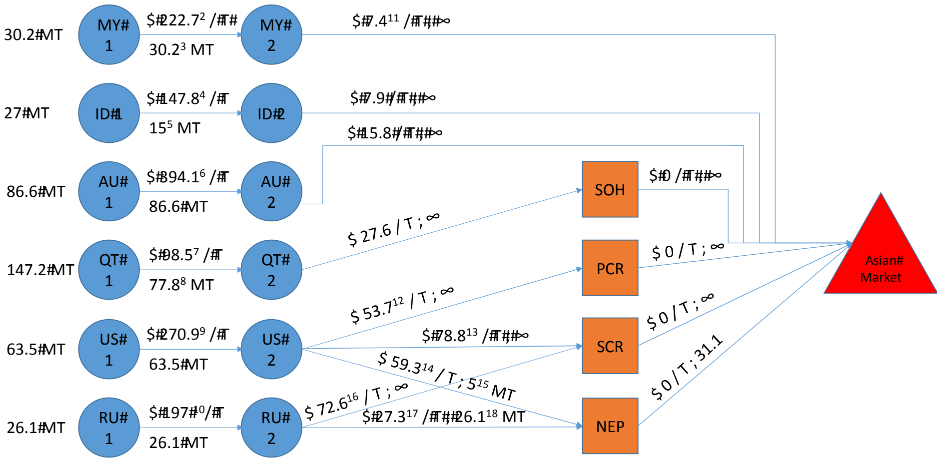

Fig. 3: Transportation Network (TN) 1

---

[2] Production costs; Source: Malaysian Gas Association (2015): 44, 45

[3] If not indicated otherwise the countries' export capacities correspond with their production capacities.

[4] Wood Mackenzie (2016)

[5] Due to a rising domestic demand and no new production sites, Indonesia limits its exports to approximately 15 MTPA; Source: EIA (2017a).

[6] Bethune (2017)

[7] Henderson (2016a): 6

[8] Although Qatar's total production capacity amounts to 147.2 MTPA, they are likely to continue to limit their exports to approximately 77.8 MTPA as previously described.

[9] Henderson (2016a): 5

[10] S&P Global Platts (2016): 6; Henderson (2016b): 5

[11] If not indicated otherwise, shipping costs are based on S&P Global Platts (2016) and Searoutes.com (2017).

[12] S&P Global Platts (2016); Searoutes.com (2017); Canal de Panama (2017b)

[13] S&P Global Platts (2016); Searoutes.com (2017); Suez Canal Authority (2017b)

[14] S&P Global Platts (2016); Searoutes.com (2017); plus costs for icebreaker support, Source: NSR Information Office (2017b)

[15] Due to limited icebreaker availability and the probable preference for Russian vessels, the capacity bottleneck for US exports through the NEP amounts to approximately 5 MTPA. Source: NSR Information Office (2017c)

[16] S&P Global Platts (2016); Searoutes.com (2017); Suez Canal Authority (2017b)

[17] S&P Global Platts (2016); Searoutes.com (2017); NSR Information Office (2017b)

[18] Limited, but sufficient transport capacity, due to limited amount of icebreaking LNG carriers and icebreakers.

Step 2: First, a maximum flow through the network is found. Therefore, Ford-Fulkerson's Max-Flow/Min-Cut Theorem is applied. The 'Cut', depicted as the dashed red line, has to go through the edges with the lowest capacities, leading to TN 2 (Fig. 4).

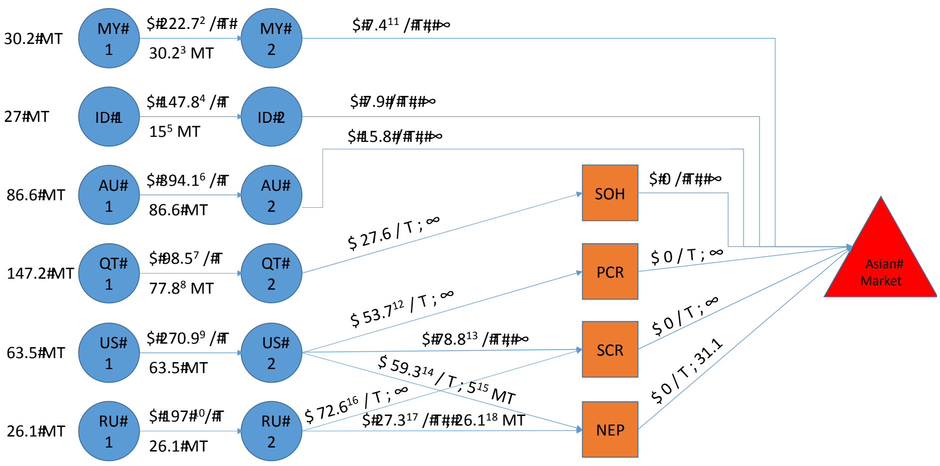

Fig. 4: TN 2

Step 3: Next, the maximum flow is sent through the network (TN 3; Fig. 5). In this scenario, demand is assumed to equal supply in the network. The numbers in the red arrows depict the actual amount of LNG (in million t) sent through the network. Because the optimality of the routes of Malaysian, Indonesian and Australian producers is predefined, due to missing alternatives, they will not be examined in the next step.

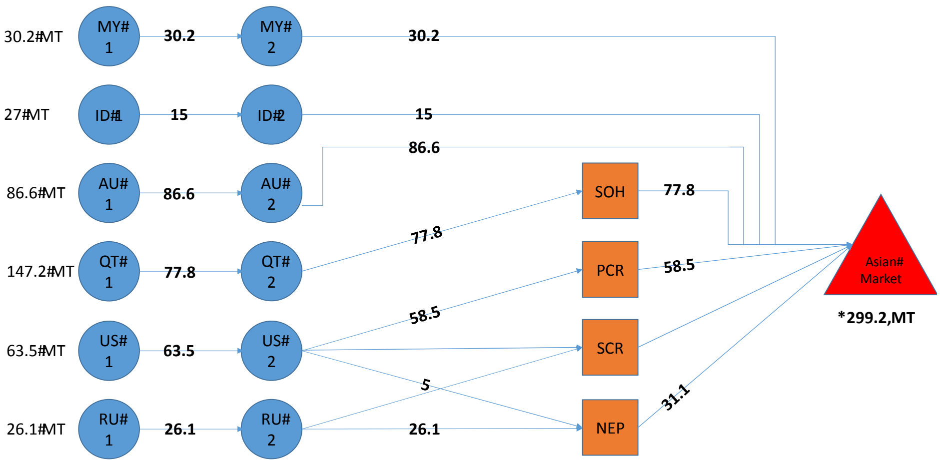

Fig. 5: TN 3

Step 4: In Fig. 6, the red arrows depict the sent flow which can be taken back. For example, there is a 'take-back' capacity of 58.5 MT through the PCR. This means that 0 - 58.5 units can possibly be taken back and reassigned to another route. The green arrows depict the remaining capacity of every route. While the assumed unlimited capacity of the SCR would permit an increase of the corresponding flow, no additional capacities can be sent through the NEP.

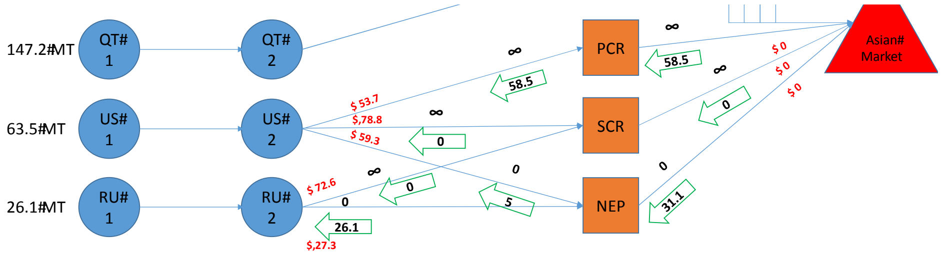

Fig. 6: TN 4

Step 5: Subsequently, the network is examined for negative cost-directed cycles. If any are identified, the flow along this cycle should be augmented. A negative cost-directed cycle exists, if the value of a unit multiplied with the cost along the cycle is negative (TN 5; Fig. 7): e.g., (-1 • 0) + (-1 • 59.3) + (+1 • 53.7) + (+1 • 0) = -5.6. It is examined whether a cost reduction can be achieved, by sending back a unit and reassigning it to another route. In this case, the reassignment of 1 US-produced ton sent from the NEP to the PCR would result in savings of $5.6.

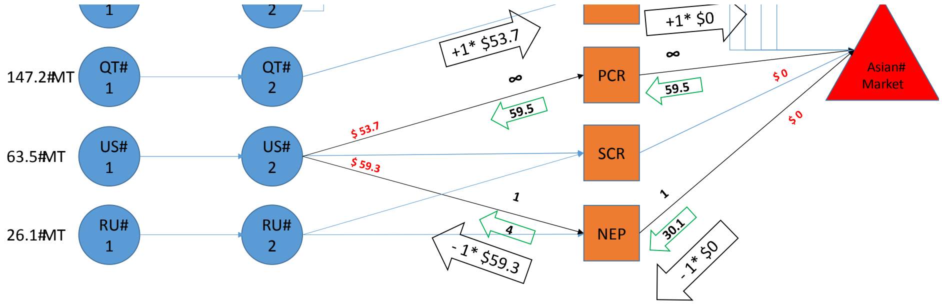

Fig. 7: TN 5

Step 6: The flow along the negative cost-directed cycle is augmented until there are no more units to be reassigned (TN 6; Fig. 8). In this case, the total cost savings that result from a shift of all US-produced units sent from the NEP to the PCR amount to $5.6 • 5 million = $28 million.

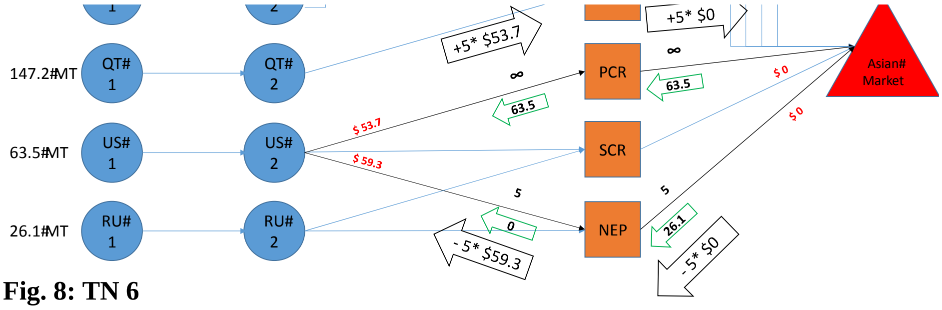

Fig. 8: TN 6

Step 7: If there are no negative cost-directed cycles left the algorithm terminates (TN 7; Fig. 9).

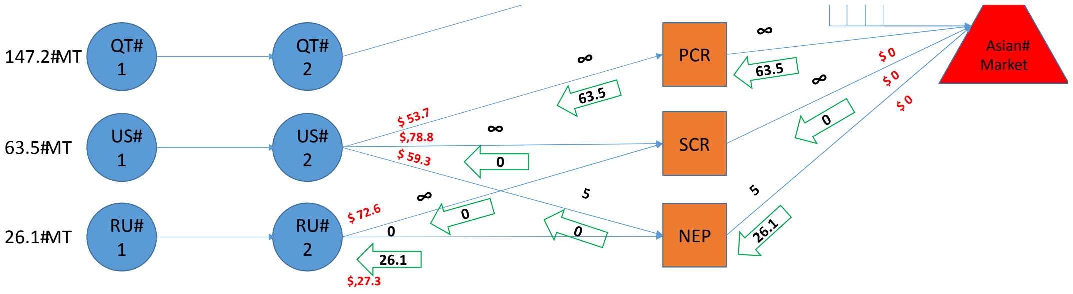

Fig. 9: TN 7

5.1.4 *Scenario 1: Route optimization – results*

Step 8: The distribution of the produced and exported volumes along the routes are cost-optimal (i.e. cost-minimizing) (TN 8; Fig. 10).

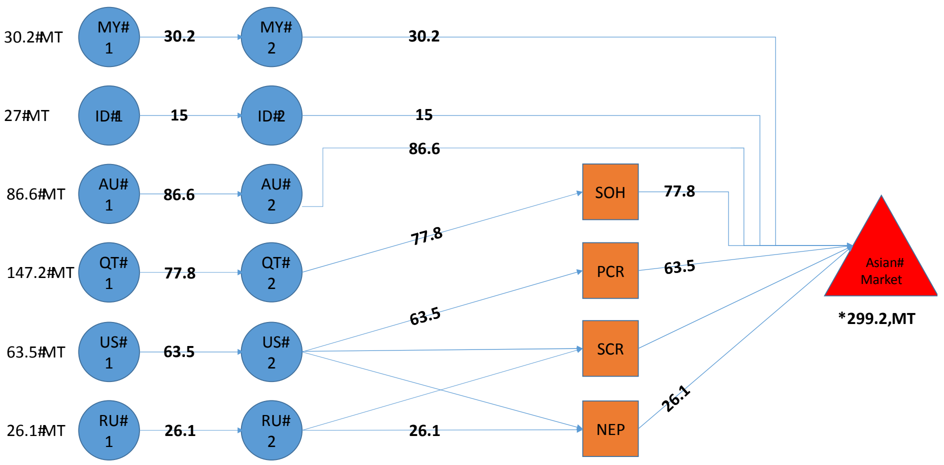

Fig. 10: TN 8

5.1.5 *Scenario 2: DV – application*

So far, it was assumed in the model that the demand of the world's leading LNG consumers in Asia equates the global supply to that region. Hence all exported volumes were bought and consumed and no competition between the producers took place. The production capacities in the model are authentic and accurate (based on Table 2). However, there are no precise figures available for the prospective demand. In 2015, the sum of Japanese, South Korean and Chinese

LNG imports amounted to 138.8 MTPA (IGU, 2016: 10). As described above, the rising demand will still be exceeded by the global oversupply. However, in this scenario, the competitiveness of the analyzed LNG producers is evaluated. The forecasted demand is distinguished: (1) *Low (DV 1)*: demand increase of 20% (166.56 MTPA); (2) *Medium (DV 2)*: demand increase of 40% (194.32 MTPA); and (3) *High (DV 3)*: demand increase of 60% (222.08 MTPA).

After the application of the Cycle-Cancelling Algorithm, the cost-optimal routes are defined for all producers. No preferences, LTCs, strategic or political considerations are involved in the commercial activities. The exporter with the least production and transportation costs is assumed to sell his entire production volume first. After the state's export capacity is depleted, the country with the second-least production and shipping costs sells its volumes etc. The total costs of each country's LNG are reported in Table 3.

Table 3: Production and transport costs of LNG - Scenario 2

States	Export capacity (MTPA)	Production costs ($/T)	Transport costs ($/T)	Total costs ($/T)
Qatar	77.8	98.5	27.6	126.1
Indonesia	15.0	147.8	7.9	155.7
Russia	26.1	197.0	27.3	224.3
Malaysia	30.2	222.7	7.4	230.1
US	63.5	270.9	53.7	324.6
Australia	86.6	394.1	15.8	409.9

Source: Own compilation, based on Fig. 3, 10.

5.1.6 Scenario 2: DV – results

DV 1: Low demand. Based on the calculations, LNG from Qatar is the most competitive product. According to this simplified model and basic economic principles, Qatar is the first state to sell all of its export volume, which amounts to 77.8 MTPA. This leads to a remaining demand of 88.76 MTPA. Indonesia, the state with the second-lowest costs/price for its LNG, will subsequently sell off its volumes of 15 MTPA. Russia is able to provide 26.1 of the 73.76 remaining MTPA. Thus a demand of 47.66 MTPA remains. After Malaysia sold its LNG exports of 30.2

MTPA, the remaining demand amounts to 17.46 MTPA and is fully supplied by the US. Thus 46.04 MTPA of US LNG and the total volume (86.6 MTPA) of Australian LNG remains unsold (TN 9; Fig. 11).

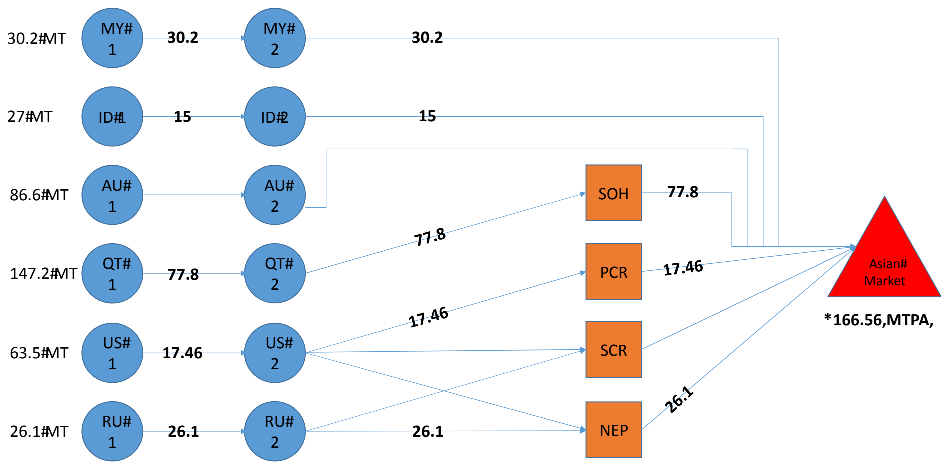

Fig. 11: TN 9 – DV 1

DV 2: Medium demand. Based on the prior reflections, a total demand of 194.32 MTPA would lead to a similar solution. In the end, after supplying the entire demand, 18.28 MTPA of the US LNG and 86.6 MTPA of the Australian LNG would remain unsold (TN 10; Fig. 12).

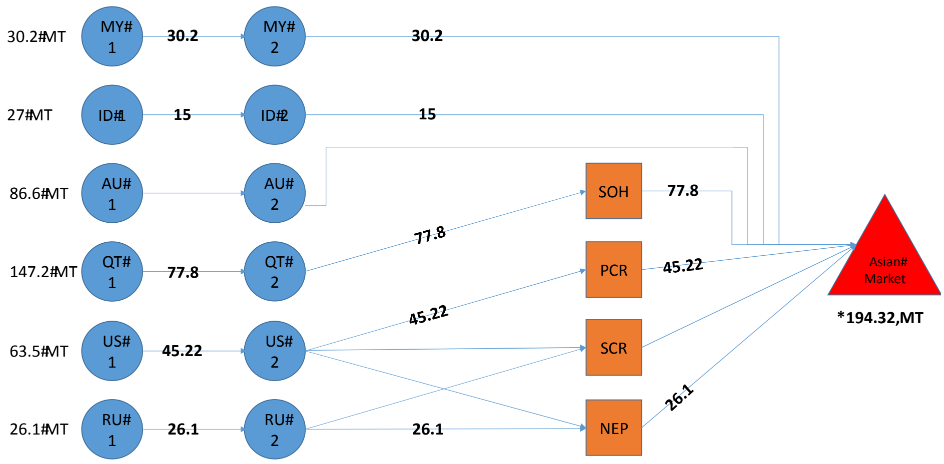

Fig. 12: TN 10 – DV 2

DV 3: High demand. In the case of an assumed demand of 222.08 MTPA all producers except Australia would have sold their entire stock. While the Australian producers could sell 9.48 MTPA, the majority of their volumes (77.12 MTPA) would remain unsold (TN 11; Fig. 13).

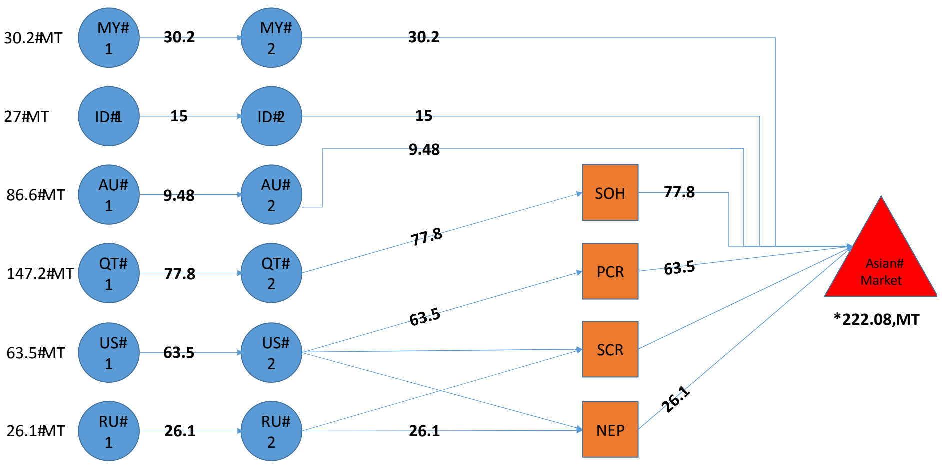

Fig. 13: TN 11 – DV 3

5.1.7 Scenario 3: Chokepoint shutdown – application and results

The model includes four relevant chokepoints for global LNG shipping: (1) The Northeast Passage; (2) the Panama Canal; (3) the Suez Canal; and (4) the Strait of Hormuz. Military conflicts, political tensions, terrorist attacks, natural catastrophes etc. may temporarily or permanently enforce the shutdown of one of these chokepoints, leading to a new optimal route distribution. Some producers would even be effectively excluded from a direct participation in the global LNG trade. Because the SCR is not part of the optimal routes in the prior model, its shutdown would not have any impacts on the other producers and is not discussed any further.

Case 1: Shutdown of NEP. In winter, the extent and strength of the ice along the Northeast Passage, especially in its Eastern part, can make shipping activities even with ice-reinforced tankers impossible. This will predominantly impact the shipping routes of the production facility located at the Yamal peninsula. Novatek plans to fulfill the company's commitments to Asian customers by shipping the LNG through the SCR. What impacts will this transport route have on the competitiveness of Yamal's LNG? Previously, a joint approximation for all Russian LNG producers was made. The cessation of the NEP would impact the Yamal LNG project exclusively. Therefore, in the following, only the corresponding production capacity is considered. A 40% rise in demand is anticipated (total demand: 194.32 MTPA).

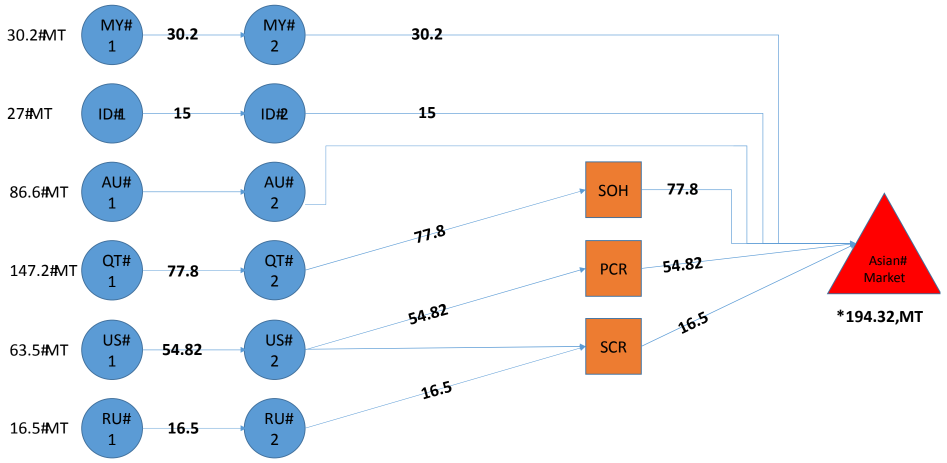

Fig. 14: TN 12 – NEP shutdown

The impacts on the competitiveness of Russian LNG are shown in Table 4 and Fig. 14 (TN 12). Although the Malaysian LNG is more competitive in this scenario, Russian producers are still able to sell their volumes due to the excessive demand and costs for US and Australian LNG.

Table 4: Production and transport costs of LNG - Scenario 3

States	Export Capacity (MTPA)	Production costs ($/T)	Transport costs ($/T)	Total costs ($/T)
Qatar	77.8	98.5	27.6	126.1
Indonesia	15.0	147.8	7.9	155.7
Malaysia	30.2	222.7	7.4	230.1
Russia	26.1	197.0	72.6	269.6
US	63.5	270.9	53.7	324.6
Australia	86.6	394.1	15.8	409.9

Source: Own compilation, based on Figs. 3, 14

Case 2: Shutdown of SOH. The Strait of Hormuz is a term that constantly is used in negotiations between the West and Iran. Iran's permanent threat to close the strait, as a response to Western sanctions has serious, measurable impacts on crude oil and gas prices. An actual closure would cut off the Persian Gulf from any maritime trading or shipping activities and thus impede Qatar's LNG exports. For this second case, the impacts of a possible SOH shutdown and the corresponding termination of Qatari LNG exports on the LNG are presented. Based on the previously assumed 40% demand increase to 194.32 MTPA, and the interception of supply from Qatar, all producers but Australia would sell all their LNG (TN 13; Fig. 15).

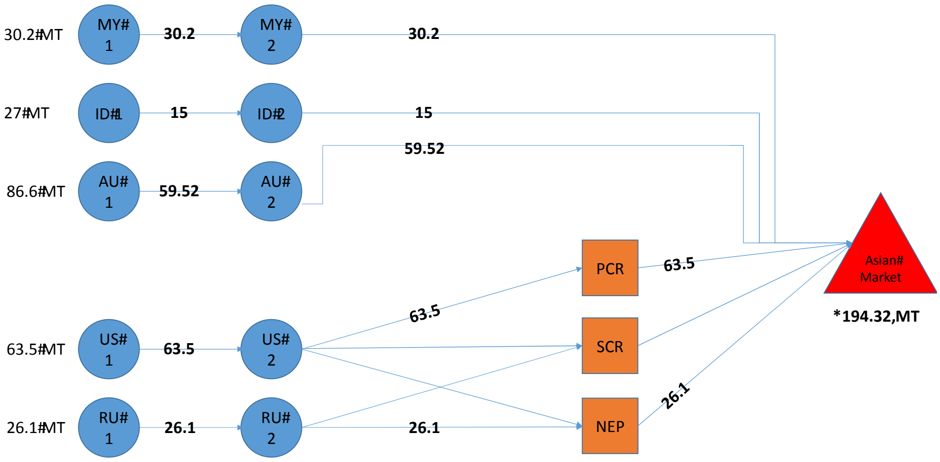

Fig. 15: TN 13 – SOH shutdown

Case 3: Shutdown of PCR. Although the shutdown of the PCR seems quite unlikely, the impacts of such an incident would be enormous and thus, are also evaluated hereafter. After the mentioned expansion of the Panama Canal, the PCR became the predominant route for US LNG exports. Approximately 98% of the US export capacities are produced on the East Coast. In the case of a PCR closure, a shipping route through the NEP (11,519 Nautical Miles, NM) or the SCR (13,924 NM) would be the best alternative. Due to the limited capacity of the NEP, the usage of both routes would be most cost-effective. The demand assumption of 194.32 MTPA is still valid. A ton of US LNG that is shipped through the NEP would have total costs of $270.9 + $59.3 = $330.2. Because of the capacity limit and the presumed preference of the state-owned and -operated Russian icebreakers to primarily fulfill their support obligation to domestic vessels. However, it is assumed that five million tons could be transported. The costs for every ton of US LNG that is shipped through the SCR amount to $270.9 + $78.8 = $349.7. Nonetheless, Australian LNG is far more costly. Based on the previous assumptions, the US will still be able to supply the remaining 45.22 MTPA (5 MTPA through the NEP and 40.22 MTPA via the SCR) (TN 14; Fig. 16).

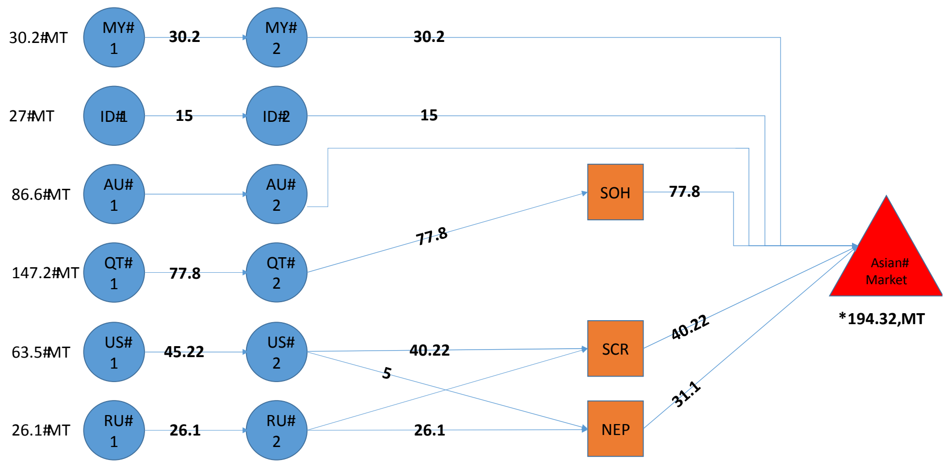

Fig. 16: TN 14 – PCR shutdown

5.1.8 Discussion of results

Firstly, a major insight of the model is the fact that the SCR is not used at all in the regular scenario with all chokepoints intact. While the US LNG is transported through the PCR, the Russian exports take place along the NEP, and Qatari tankers pass through the SOH, the other considered producers can ship their cargo directly to Asia. However, it should be kept in mind that this is a very simplified model, taking into account only the Asian consumer market and only the major LNG producers.

Secondly, the demand variation scenarios depict a supply-side competition, considering the costs of transportation and production. The results show that the Australian und US LNG exports are the least competitive, primarily due to the high production costs. Again, the model is very simplified, not fully considering the sunk costs of the producers.

Thirdly, a shutdown of the NEP, as it occurs during the winter months, shifts all Russian exports through the SCR and almost triples the transportation costs. Nonetheless, the Russian exports remain competitive, if compared to the US or Australia. A shutdown of the SOH, resulting in a cut-off of Qatari supplies, benefits the other market participants who occupy Qatar’s market share. There is no imminent threat to the LNG supply security. If the PCR closes down, the US exports would be rerouted trough the NEP and SCR with a slight cost increase.

5.2 Impacts on price arbitrage

In 1882, Joseph L. F. Bertrand introduced a competition model, which describes the interactions and interdependencies taking place between at least two suppliers who can choose the price for a homogeneous good and consumers who can choose the quantities they want to purchase. The suppliers have the objective to maximize their profits. By assumption, they do not cooperate. The demanded quantity is negatively correlated with the price. It is further assumed that the consumers purchase the least-expensive good, and that the price is the only distinguishing feature. If supplier A chooses a higher price then supplier B, the consumers will purchase only B's commodity, and vice versa. Finally, it is assumed that the suppliers will split the market shares in case they set exactly the same price (Narahari et al., 2009: 21,22).

The price that can be set by the suppliers is limited by their marginal costs, provided that no supplier will sell at a loss. The conclusion is that the suppliers will compete until one of them is not willing or able to decrease his price any further because it would undercut his marginal costs. Therefore, the consumer whose product is more competitive will dominate the entire market and set a price that equals the marginal costs of his closest competitor (or rather one marginal unit less). With regard to the LNG market and the previously introduced model, it is assumed that the LNG is a fully homogeneous product and perfect substitute. Based on the previous assumptions a demand amounting to 194.32 MTPA is defined. It is further assumed that there are only six producers, with different marginal costs and quantities, and multiple purchasers, represented in a unified 'Asian Market', whose decision is solely based upon the price difference of the product. The consumers will prefer to buy LNG of any producer as long as the price is lower than for the other quantities that are available in the market.

If total availability of information is assumed, and all exporters are therefore aware of the other player's production costs and the exact level of LNG demand in Asia, a Bertrand competition will take place. Knowing that the demand equals 194.32 MTPA, the states with the lowest production and transportation costs that can supply this amount individually or jointly will set a price that equals the marginal costs of the next best competitor. This means that Qatar will sell its total export capacity of 77.8 MTPA, Indonesia 15 MTPA, Russia 26.1 MTPA, Malaysia 30.2 MTPA, the US 45.22 MTPA at a price per ton amounting to the marginal costs of the competitor Australia, \$409.9 – *C* (Fig. 17).

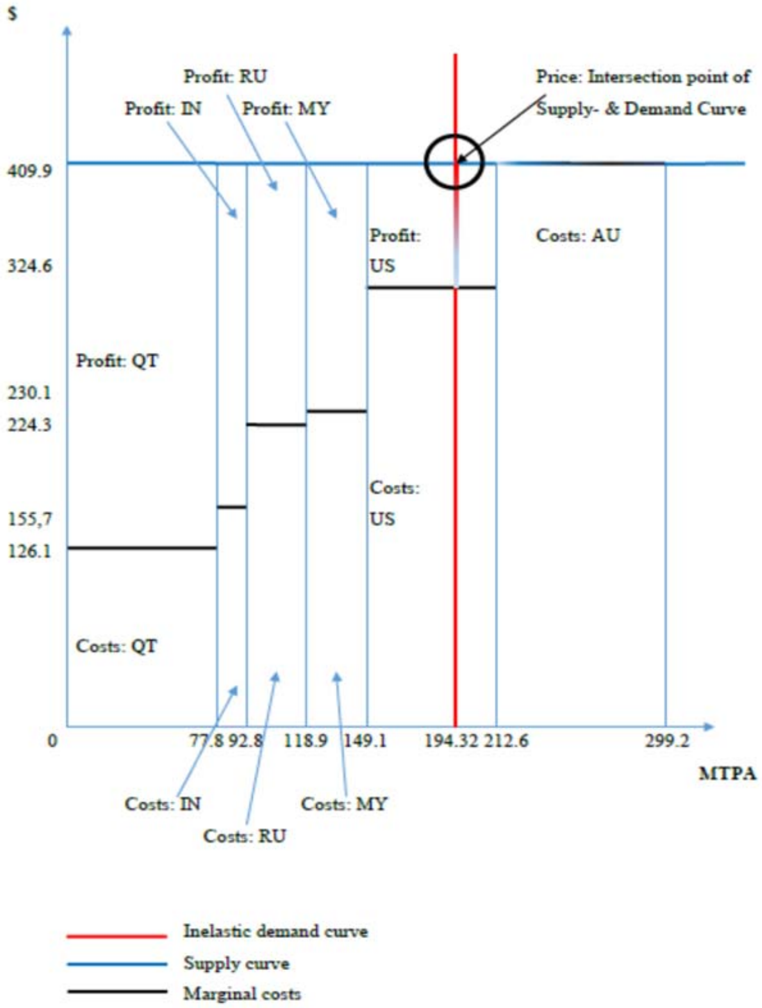

Fig. 17: Supply and demand curve - Impacts on pricing

In the model, a state is depicted as it may occur before an FID on an E&P project. It is assumed that there are no pre-existing and subsequent projects, the demand is inelastic, amounting to 194.32 MTPA, and that there is total information. In this case, the optimized capacities and the arbitrage modeling in a Bertrand competition have resulted in a price amounting to \$409.9 per ton. This equals to (409.9/49.2579) \$8.32 / MMBtu (Fig. 17). In November 2016, the price for 1 MMBtu amounted to \$5.9 on the Japanese spot market (Table A1). According to the model (Fig. 17), a price increase of approximately 41% until 2020 is projected.

6 Conclusions

The NEP is a crucial element in the supply chain of Russian LNG producers. It opens a shorter and less expensive alternative to the SCR for Russian LNG producers. Because most of the Russian gas fields are located in North-West Siberia, such a sea route is a necessity for any large-scale LNG export aspirations. A shutdown of the NEP nearly triples the transportation costs to the Asian markets when using the SCR instead. However, the NEP is hardly relevant for other LNG-producing countries for exports to Asia. Since the expansion of the Panama Canal in 2016, all North- and South-American producers will prefer the usage of the PCR as the shortest and most cost-efficient route to Asia. Nevertheless, the crucial element for the competitiveness of various worldwide projects remain the projects' break-even costs. In our model, a simplifying assumption was made that is not valid in the real LNG market. Despite being generally unprofitable, Australian and US producers will continue to put large quantities on the market, due to the majority of their costs being sunk- and not marginal costs – if the marginal revenues exceed the marginal costs. Unless some of the producers will limit their export capacities either individually or jointly, supply will by far exceed demand. Due to the scope of the investigation the LNG market is considerably simplified. Unlike in the model, the unprofitable suppliers will proceed to sell their volumes at a loss, due to the high amount of sunk costs. As mentioned earlier, the model rather depicts a snapshot of a pre-negotiation state than the present market dynamics. Another central element for a more sophisticated model is the reproduction of a market state, including LTCs, spot sales and an elastic demand curve. Further, a more detailed assessment of the parameters might facilitate a more accurate forecast on achievable cost savings with regard to the NEP. However, the objective of the modeling in this study was to initially demonstrate the usefulness of applying methods on LNG shipping routes with regard to a temporally ice-free NEP, and to pave the way for further research. Finally it can be stated, that although there are other factors to consider, Russia's market entry, largely enabled through ice-free shipping along the NEP, does effect both price and competition.

Acknowledgments

The first author gratefully acknowledges the financial research support from the Verbundnetz Gas AG.

References

Ahuja, R., Magnanti, T., Orlin, J. and Reddy, M. (1995), Applications of network optimization, *Handbook in Operations Research and Management Science,* 7, 1-83.

Ammann, D. (2010), *King of Oil: Marc Rich*. Zurich, Switzerland: Orell Füssli Verlag.

Avango, D., Hacquebord, L. and Wrakberg, U. (2014), Industrial extraction of Arctic natural resources since the sixteenth century: technoscience and geo-economics in the history of northern whaling and mining, *Journal of Historical Geography,* 44, 15-30.

Bethune, G. (2015), Australian LNG set to ride out low price storm, report. *AOG, Australian Oil & Gas Exhibition & Conference,* [Online] URL: http://aogexpo.com.au/australian-lng-set-to-rise-out-low-price-storm-report/ [retrieved February 5, 2017].

Bertsekas, D. (1998), *Network Optimization: Continuous and Discrete Models*. Cambridge, Massachusetts, USA: The MIT Press.

Buixadé Farré, A., Stephenson, S., Chen, L., Czub, M., Dai, Y., Demchev, D., Efimov, Y., Graczyk, P., Grythe, H., Keil, K., Kivekäs, N., Kumar, N., Liu, N., Matelenok, I., Myksvoll, M., O'Leary, D., Olsen, J., Pavithran, S., Petersen, E., Raspotnik, A., Ryzhov, I., Solski, J., Suo, K., Troein, C., Valeeva, V., van Rijckevorsel, J. and Wighting, J. (2014), Commercial Arctic shipping through the Northeast Passage: routes, resources, governance, technology, and infrastructure, *Polar Geography,* 37, 4, 298-324.

Canal de Panama (2017a), Main Page > Expansion Program [Online] URL: https://www.pancanal.com/eng/op/tariff/1010-0000-Rev20160708.pdf [retrieved February 5, 2017].

Canal de Panama (2017b), Main Page > Maritime Services > Marine Tariff > Tolls [Online]URL: https://www.pancanal.com/eng/op/tariff/1010-0000-Rev20160708.pdf [retrieved February 5, 2017].

Cormen, T., Leiserson, C., Rivest, R. and Stein, C. (2009), *Introduction to Algorithms.* Cambridge, Massachusetts, USA: The MIT Press.

Dijkstra, E. (1959), A Note on Two Problems in Connexion with Graphs, *Numerische Mathematik,* 1, 269-271.

Egging, R. and Holz, F. (2016), Risks in global natural gas markets: Investment, hedging and trade, *Energy Policy*, 94, 468-479.

EIA, U.S. Energy Information Administration (2017a), Indonesia: International Energy Data and Analysis, [Online] URL: https://www.eia.gov/beta/international/analysis_includes/countries_long/Indonesia/indonesia.pdf [retrieved February 5, 2017].

Ellis, B. and Brigham, L. (2009), Arctic Marine Shipping Assessment 2009 Report, Arctic Council, [Online] URL: https://oaarchive.arctic-council.org/handle/11374/54 [retrieved December 27, 2016].

Ford, L. and Fulkerson, D. (1956), Maximal Flow through a Network, *Canadian Journal of Mathematics,* 8, 399-404.

Foy, H. (2017), Russia’s Yamal gas project navigates ice and sanctions, *Financial Times*, [Online] URL: https://www.ft.com/content/8412ba8c-6ace-11e7-b9c7-15af748b60d0 [retrieved October 20, 2017].

GECF, Gas Exporting Countries Forum (2017), GECF Global Gas Outlook 2040, [Online] URL: https://www.gecf.org/_resources/files/events/gecf-global-gas-outlook-2040--- synopsis/gecf-global-gas-outlook-2040---synopsis.pdf [retrieved January 24, 2017].

IGU, International Gas Union (2016), 2016 World LNG Report, [Online] URL: http://www.igu.org/publications/2016-world-lng-report [retrieved January 5, 2017].

IEA, International Energy Agency (2016), World Energy Outlook 2016 Executive, [Online] URL: https://www.iea.org/publications/freepublications/publication/WorldEnergyOutlook2016ExecutiveSummaryEnglish.pdf [retrieved January 1, 2017].

Henderson, J. (2016a), The supply outlook: Australia and the USA, *Oxford Energy Forum,* August 2016: Issue 106, 4-5, Oxford Institute for Energy Studies, Oxford, UK.

Henderson, J. (2016b), Novatek leads the advance of Russian LNG, *Oxford Energy Forum,* November 2016: Issue 107, 22-24, Oxford Institute for Energy Studies, Oxford, UK.

Humpert, M. and Raspotnik, A. (2012), The future of Arctic shipping, *Port Technology International,* [Online] URL: https://www.porttechnology.org/technical_papers/the_future_of_arctic_shipping [retrieved January 4, 2017].

Jiang, J. (2016), China's urban residential carbon emission and energy efficiency policy, *Energy,* 109, 866-875.

Kim, J. et al., (2016), Korean public's preference for supply security of oil and gas and the impact of protest bidders, *Energy Policy,* 89, 202-213.

Klein, M. (1967), A primal method for minimal cost flows with applications to the assignment and transportation problems, *Management Science,* 14, 3, 205-220.

Knuth D. (1976), A generalization of Dijkstra's algorithm, *Information processing letters,* 6, 1, 1-5, Computer Science Department, Stanford University.

Kwok, W. (2012), Strait of Hormuz: the world's LNG choke point, *Petroleum Economist,* 5. January 2012, [Online] URL: http://www.petroleum-economist.com/articles/midstream-downstream/lng/2012/strait-of-hormuz-the-worlds-lng-choke-point [retrieved February 6, 2017].

Kwok, R. and Rothrock, D. (2009), Decline in Arctic sea ice thickness from submarine and Ice Sat records: 1958–2008. *Geophysical Research Letters*, Vol. 36, Issue 15.

Luebbecke, M. (2015), Einführung in Operations Research. *Chair of Operations Research, RWTH Aachen University*, Aachen, Germany [Online] URL: https://www3.elearning.rwth-aachen.de/ss15/15ss-06010/Lists/StructuredMaterials/Vorlesung/20150506.pdf [retrieved February 2, 2017].

Malaysian Gas Association (2015), Malaysia: Natural Gas Industry Annual Review, [Online] URL: http://www.malaysiangas.com/portal/document/publication/1451274416_Annual_Rev.pdf [retrieved February 5, 2017].

METI, Ministry of Economy, Trade and Industry (2016a), Main Page > Statistics > Spot LNG-Price Statistics (November 2016) > Overview of Statistics [Online] URL: http://www.meti.go.jp/english/statistics/sho/slng/index.html [retrieved January 1, 2017].

METI, Ministry of Economy, Trade and Industry (2016b), Strategy for LNG Market Development: creating flexible LNG market and developing an LNG trading hub in Japan, [Online] URL: http://www.meti.go.jp/english/press/2016/pdf/0502_01b.pdf [retrieved January 1, 2017].

METI, Ministry of Economy, Trade and Industry (2016c), Japan’s Energy Plan, [Online] URL: http://www.meti.go.jp/english/publications/pdf/EnergyPlan_160614.pdf [retrieved January 7, 2017].

Moon, D., Kim, D. and Lee, E. (2015). A Study on Competitiveness of Sea Transport by Comparing International Transport Routes between Korea and EU, *The Asian Journal of Shipping and Logistics,* 31, 1, 1-20.

Mokhatab, S., Mak, J., Valappil, J. and Wood, D. (2013), *Handbook of Liquefied Natural Gas*. Gulf Professional Publishing.

Motomura, M. (2014), Japan’s need for Russian oil and gas: A shift in energy flows to the Far East, *Energy Policy*, 74, 68-79.

Nagy, R. (2003), Minimum Cost Flow Problems. Department of Industrial Engineering, University at Buffalo, Buffalo, NY. [Online] URL: http://www.acsu.buffalo.edu/%7Enagi/courses/684/9.mincost.pdf [retrieved February 2, 2017].

Narahari, Y., Garg, D., Narayanam, R. and Prakash, H. (2009), *Game Theoretic Problems in Network Economics and Mechanism Design Solutions.* London, England: Springer.

Novatek (2017a), Main Page > Business > Yamal LNG > Project implementation [Online] URL: http://www.novatek.ru/en/business/yamal-lng/yamal_current/ [retrieved January 10, 2017].

Novatek (2017b), Main Page > Investor Relations > Events > Archive > Novatek signs long-term LNG contract with Shell [Online] URL: http://novatek.ru/en/press/releases/index.php?id_4=972 [retrieved January 10, 2017].

Novatek (2017c), Main Page > Investor Relations > Events > Archive > Novatek concludes long-term LNG contract with Engie [Online] URL: http://www.novatek.ru/en/press/releases/index.php?id_4=970 [retrieved January 10, 2017].

NSR, Northern Sea Route Information Office (2017a), Main Page > NSR > Ice concentration [Online] URL: http://www.arctic-lio.com/nsr_ice [retrieved January 26, 2017].

NSR, Northern Sea Route Information Office (2017b), Main Page > NSR > Admittance criteria and Icebreaker Tariffs [Online] URL: http://www.arctic-lio.com/nsr_tariffsystem [retrieved February 5, 2017].

NSR, Northern Sea Route Information Office (2017c), Main Page > NSR > Icebreakers Assistance [Online] URL: http://www.arctic-lio.com/nsr_icebreakersassistance [retrieved February 5, 2017].

Paraskova, T. (2017), Putin says Russia will become world's top LNG producer. *The Oil Price.* 2 April, 2017. [Online] URL: https://oilprice.com/Energy/Natural-Gas/Putin-Says-Russia-Will-Become-Worlds-Top-LNG-Producer.html [retrieved December 16, 2017].

Ragner, C. (2008), *The Northern Sea Route. The Barents – A Nordic Borderland*, Stockholm, Sweden: Arena Norden.

Reeves, R., Ewins, P., Agbayani, S., Heide-Jorgsensen, M., Kovacs, K., Lydersen, C., Suydam, R., Elliott, W., Polet, G., van Dijk, Y. and Blijleven, R. (2014), Distribution of endemic cetaceans in relation to hydrocarbon development and commercial shipping in a warming Arctic, *Marine Policy,* 44, 375-389.

Schach, M. and Madlener, R., (2017), Impacts of an Ice-Free Northeast Passage on LNG Markets and Geopolitics, *FCN Working Paper* No. 4/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University.

Searoutes.com (2017), [Online] URL: http://www.searoutes.com/routing?speed=13&panama=true&suez=true&kiel=true&ne=true&nw=true [retrieved February 5, 2017].

Shim, C. and Hong, J. (2016), Impact of a national plan for future electricity supply on ambient air quality in South Korea, *Energy Policy,* 88, 278-288.

Stephenson, S., Brigham, L. and Smith, L. (2013), Marine accessibility along Russia's Northern Sea Route. *Polar Geography*, 37(2), 111–133.

Stern, J. (2016), The new Japanese LNG strategy: a major step towards hub-based gas pricing in Asia, *Oxford Energy Comment*, June 2016, Oxford Institute for Energy Studies, Oxford, UK.

Suez Canal Authority (2017a), Main Page > Navigation > Navigation Statistics [Online] URL: http://www.suezcanal.gov.eg/English/Navigation/Pages/NavigationStatistics.aspx [retrieved February 6, 2017].

Suez Canal Authority (2017b), Main Page > The Canal > Canal Characteristics [Online] URL: https://www.suezcanal.gov.eg/calc.aspx [retrieved February 6, 2017].

S&P Global Platts (2016), *LNG Daily*. 23. September 2016 [Online] URL:https://online.platts.com/PPS/P=m&s=1029337384756.1478827&e=1474933439284.5 32211100888081207/ [retrieved January 2, 2017].

Verny, J. and Grigentin, C. (2009), Container Shipping on the Northern Sea Route, *Int. J. Production Economics*, 122, 107-117.

Wayne K. (2004), Algorithms and Data Structures: Max Flow, Min Cut, Department of Computer Sciences, Princeton University, Princeton, NJ, USA. [Online] URL: http://www.cs.princeton.edu/courses/archive/spr04/cos226/lectures/maxflow.4up.pdf [retrieved February 6, 2017].

Wood Mackenzie (2016), What is the status of various Indonesian LNG projects? *Gastech-News.* 22 February, 2016 [Online] URL: http://www.gastechnews.com/lng/what-is-the-status-of-various-indonesian-lng-projects/ [retrieved February 5, 2017].

Yamal LNG (2015a), Main Page > Press Center > 2015 > Gazprom Marketing & Trading Singapore and Yamal Trade conclude long-term LNG supply agreement [Online] URL: http://yamallng.ru/en/press/news/311/ [retrieved January 9, 2017].

Yamal LNG (2014b), Main Page > Press Center > 2014 > Binding contract on LNG supply concluded with CNPC [Online] URL: http://yamallng.ru/en/press/news/283/ [retrieved January 9, 2017].

Yamal LNG (2013c), Main Page > Press Center > 2013 > Yamal LNG and Gas Natural Fenosa sign long-term LNG supply contract [Online] URL: http://yamallng.ru/en/press/news/283/ [retrieved January 9, 2017].

Yamal LNG (2015d), Main Page > Press Center > 2015 > Yamal LNG and Fluxys LNG sign contract for LNG transshipment services at Zeebrugge LNG terminal [Online] URL: http://yamallng.ru/en/press/news/310/ [retrieved January 9, 2017].

Yonhap News Agency (2016), S. Korea to invest 42 tln won in renewable energy industry by 2020, *Yonhap News Agency.* 05. July, 2016 [Online] URL: http://english.yonhapnews.co.kr/news/2016/07/04/0200000000AEN20160704008951320.html?input=www.tweeter.com [retrieved February 17, 2017].

Appendix

Table A1: Japan's spot LNG prices (2014-2016) [$/MMBtu]

Year	Month	Contract-based	Arrival-based
2014	3	18.3	-
	4	16.0	18.3
	5	14.8	16.3
	6	13.8	15.0
	7	11.8	13.8
	8	11.4	12.5
	9	13.2	11.3
	10	15.3	12.4
	11	14.4	14.3
	12	11.6	15.1
2015	1	10.2	13.9
	2	7.6	10.7
	3	8.0	7.6
	4	7.6	7.9
	5	-	-
	6	7.6	7.6
	7	7.9	-
	8	8.1	7.7
	9	7.4	7.7
	10	7.6	7.9
	11	7.4	7.5
	12	7.4	7.5
2016	1	7.1	7.9
	2	6.5	6.9
	3	-	6.8
	4	4.2	5.8
	5	4.1	4.3
	6	-	4.5
	7	5.8	6.0
	8	-	5.4
	9	5.7	-
	10	6.1	5.7
	11	7.0	5.9

Source: METI (2016a)

FCN | Future Energy Consumer Needs and Behavior

E.ON Energy Research Center

RWTH AACHEN UNIVERSITY

List of the latest FCN Working Papers

2017

Demikhovskiy M., Madlener R., Garbuzova-Schlifter M., Golov R. (2017). Energy Performance Contracting in Russia: A Real Options Approach on Project Valuation, FCN Working Paper No. 1/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, January.

Frieling J., Madlener R. (2017). Fueling the US Economy: Energy as a Production Factor from the Great Depression Until Today, FCN Working Paper No. 2/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February (revised May 2017).

Risthaus K., Madlener R. (2017). Economic Analysis of Electricity Storage Based on Heat Pumps and Thermal Storage Units in Thermal Power Plants, FCN Working Paper No. 3/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, March.

Schach M., Madlener R. (2017). Impacts of an Ice-Free Northeast Passage on LNG Markets and Geopolitics, FCN Working Paper No. 4/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, April.

Goebbels L., Madlener R. (2017). Resilience of a Modular Expansion Microgrid: Concepts, Indicators and Performance Evaluation, FCN Working Paper No. 5/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Goebbels L., Madlener R. (2017). Investment Valuation of a Modular Expansion Microgrid: A Real Options Analysis, FCN Working Paper No. 6/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Frieling J., Madlener R. (2017). The Turning Tide: How Energy Has Driven the Transformation of the British Economy Since the Industrial Revolution, FCN Working Paper No. 7/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, June.

Walgern J., Peters L., Madlener R. (2017). Economic Evaluation of Maintenance Strategies for Offshore Wind Turbines Based on Condition Monitoring Systems, FCN Working Paper No. 8/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July.

Westendorf D., Madlener R. (2017). Bundling of Distributed Battery Storage Units as a Virtual Storage Swarm, FCN Working Paper No. 9/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Schmitz H., Madlener R. (2017). Direct and Indirect Rebound Effects in German Households: A Linearized Almost Ideal Demand System Approach, FCN Working Paper No. 10/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Hof E., Madlener R., Kukla P. (2017). Power-to-Gas for Rail Transport: Economic Evaluation and Concept for the Cost-Optimal Hydrogen Supply, FCN Working Paper No. 11/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Schach M., Madlener R. (2017). Impacts of an Ice-Free Northeast Passage on LNG Trading: Transport Routes and Optimal Capacity Planning, FCN Working Paper No. 12/2017, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

2016

Frieling, J., Madlener, R. (2016). Estimation of Substitution Elasticities in Three-Factor Production Functions: Identifying the Role of Energy, FCN Working Paper No. 1/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, March (revised September 2016).

Al-Saad F., Madlener R. (2016). The Role of Shale Gas in the EU Decarbonization Process, FCN Working Paper No. 2/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, March.

De Graaf X., Madlener R. (2016). Optimal Time-Dependent Usage of Salt Cavern Storage Facilities for Alternative Media in Light of Intermittent Electricity Production and Carbon Sequestration, FCN Working Paper No. 3/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, April.

Weida J., Kumar S., Madlener R. (2016). Economic Viability of Grid-Connected Solar PV and Wind Power Systems in Germany: A Multi-Region Analysis, FCN Working Paper No. 4/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Franzen S., Madlener R. (2016). Optimal Expansion of a Hydrogen Storage System for Wind Power: A Real Options Analysis, FCN Working Paper No. 5/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, June.

Hammann E., Madlener R., Hilgers C. (2016). Economic Feasibility of Compressed Air Energy Storage Systems: A Real Options Approach, FCN Working Paper No. 6/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July.

Kirmas A., Madlener R. (2016). Economic Viability of Second-Life Electric Vehicle Batteries for Energy Storage in Private Households, FCN Working Paper No. 7/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July.

Peters L., Madlener R. (2016). Economic Evaluation of Maintenance Strategies for Ground-Mounted Solar Photovoltaic Plants, FCN Working Paper No. 8/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Falcke L.F., Madlener R. (2016). Potential Impacts of the Planned Market Stability Reserve on Speculators' Behavior in the EU Emissions Trading System. FCN Working Paper No. 9/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Glensk B., Madlener R. (2016). Evaluating the Enhanced Flexibility of Lignite-Fired Power Plants: A Real Options Analysis, FCN Working Paper No. 10/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Galassi V., Madlener R. (2016). Some Like it Hot: The Role of Environmental Concern and Comfort Expectations in Energy Retrofit Decisions, FCN Working Paper No. 11/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Köllner L., Madlener R. (2016). Market Evaluation for Virtual Power Plants in Europe with a Special View at Incentive-Based Policy Instruments, FCN Working Paper No. 12/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, October.

Broering H., Madlener R. (2016). Beyond Grid Parity: Conceptualization of the Merit of Cloud Energy Storage for Prosumers, FCN Working Paper No. 13/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Madlener R., Broering H. (2016). Direct Marketing and Cloud Energy Storage in Liberalized Markets: The German Regulatory Framework as a Benchmark, FCN Working Paper No. 14/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Broering H., Madlener R. (2016). Simulating the Spatial Heterogeneity of Cloud-based Prosumer Battery Systems, FCN Working Paper No. 15/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Madlener R., Broering H. (2016). The Benefits of Perfect Foresight in Prosumer Battery Clouds, FCN Working Paper No. 16/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Heesen F., Madlener R. (2016). Consumer Behavior in Energy-Efficient Homes: The Limited Merits of Energy Performance Ratings as Benchmarks, FCN Working Paper No. 17/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Atasoy A. T. (2016). Behavioral Responses of Green Builders to Discontinuous Certification Schemes, FCN Working Paper No. 18/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Galassi V., Madlener R. (2016). Shall I Open the Window? An Experiment on Effort and Habits in Thermal-Comfort Adjustment Practices, FCN Working Paper No. 19/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Von Hülsen H., Madlener R. (2016). Techno-Economic Selection and Evaluation of Generation-Storage Portfolios for Partially Self-Sufficient Energy Municipalities, FCN Working Paper No. 20/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Tran J., Madlener R., Fuchs A. (2016). Economic Optimization of Electricity Supply Security in Light of the Interplay Between TSO and DSO, FCN Working Paper No. 21/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December (revised May 2017).

Gürses G., Garrison J., Madlener R., Demiray T. (2016). Economic and Operational Assessment of Reserve Methods and Metrics for Electric Grids with High Shares of Renewables, FCN Working Paper No. 22/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December (revised May 2017).

Löbberding J., Madlener R. (2016). Techno-Economic Analysis of Micro Fuel Cell Cogeneration and Storage, FCN Working Paper No. 23/2016, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

FCN Working Papers have been published since 2008 and are free of charge. They can mostly be downloaded in pdf format from the FCN / E.ON ERC Website (www.eonerc.rwth-aachen.de/fcn) and the SSRN Website (www.ssrn.com), respectively. Alternatively, they may also be ordered as hardcopies from Ms Sabine Schill (Phone: +49 (0) 241-80 49820, E-mail: post_fcn@eonerc.rwth-aachen.de), RWTH Aachen University, Institute for Future Energy Consumer Needs and Behavior (FCN), Chair of Energy Economics and Management (Prof. Dr. Reinhard Madlener), Mathieustrasse 10, 52074 Aachen, Germany.