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Research paper

Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon

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ABSTRACT

As a result of particular locations of large-scale energy producers and increases in energy demand, transporting energy has become one of the key challenges of energy supply. For a long-distance ocean transportation, transfer of energy carriers via ocean tankers is considered as a decent solution compared to pipelines. Due to cryogenic temperatures of energy carriers, heat leaks into storage tanks of these carriers causes a problem called boil-off gas (BOG). BOG losses reduce the quantity of energy carriers, which affects their economic value. Therefore, this study proposes to examine the effects of BOG economically in production and transportation phases of potential energy carriers produced from natural gas, namely; liquefied natural gas (LNG), dimethyl-ether (DME), methanol, liquid ammonia (NH_3), and liquid hydrogen (H_2). Mathematical approach is used to calculate production and transportation costs of these energy carriers and to account for BOG as a unit cost within the total cost. The results of this study show that transportation costs of LNG, liquid ammonia, methanol, DME, and liquid hydrogen from natural gas accounting for BOG are 0.74 \$/GJ, 1.09 \$/GJ, 0.68 \$/GJ, 0.53 \$/GJ, and 3.24 \$/GJ, respectively. DME and methanol can be more economic compared to LNG to transport the energy of natural gas for the same ship capacity. Including social cost of carbon (SCC) within the total cost of transporting the energy of natural gas, the transportation cost of liquid ammonia is 1.11 \$/GJ, whereas LNG transportation cost rises significantly to 1.68 \$/GJ at SCC of 137 \$/t CO_2 eq. Consequently, liquid ammonia becomes economically favored compared to LNG. Transportation cost of methanol (0.70 \$/GJ) and DME (0.55 \$/GJ) are also lower than LNG, however, liquid hydrogen transportation cost (3.24 \$/GJ) is still the highest even though the increment of the cost is about 0.1% as SCC included within the transportation cost.

1. Introduction

The energy of natural gas can be transported in large-scale quantity either by pipelines commonly in gaseous forms or by chemicals commonly in liquefied forms. Transporting the energy of natural gas by pipeline is not considered commercially feasible for distance over 2000 km, however, liquefied forms such as liquefied natural gas (LNG) becomes more advantageous for long distances (Pospíšil et al., 2019). Liquefied natural gas is the most common form to export the energy of natural gas from the countries having large proven natural gas reserves such as Qatar and Australia. For example, Qatar converts 70% of it produced natural gas yearly into LNG for exportation purposes (Shah, 2017). LNG is favorable to be used to transport the energy of natural gas due to the reduction in the volume of about 600 times compared to gaseous forms (Nwaoha and Wood, 2014). However, transporting the energy as LNG has two unfavorable disadvantages that have made LNG exporting countries to invest more in transporting sector to find alternatives for higher efficient transport methods; (i) LNG has a low boiling temperature of about −162 °C and (ii) LNG contains carbon atoms which pollute the environment (Kurle et al., 2017). A liquefied form with a low boiling temperature continuously loses some portion of its mass due to temperature difference between the liquefied energy carriers and the ambient, these losses are called boil-off gas (BOG) (Jia et al., 2020). BOG is an unavoidable problem when the energy of natural gas is transported in a liquefied form. Researchers proposed different solutions to eliminate the generated BOG, For example, a reliquefication facility that captures the generated BOG and sends back to storage tanks or used as fuel for the propulsion system of the ship (Moon et al., 2007). Whereas other researchers proposed to transport the energy of natural gas by other liquefied energy forms such as ammonia, methanol, and hydrogen to reduce the production of BOG (Seddon, 2006a). One of the options to prevent

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BOG generation during ocean transportation is to use pressurized tanks. Pressurized tanks can keep BOG inside the tank and have invulnerable behavior against leakage. However, for large quantities of energy carriers, to store these liquefied energy carriers without BOG ventilation, several pressure cylinders are needed to be installed in the ship. This approach does not meet the design concept of the ship because of the disadvantages of wasting ship space, increasing the tank weight, and increasing operational and instruments complexity. Thus, installing non-pressure tanks is an alternative approach for large quantity energy carriers and such tanks meet the (IMO) classification for ocean transportation tanks (Chang, 2017).

Furthermore, the amount of BOG generated during LNG ocean transport is dependent on the voyage length and it is around 2.5% to 3% of the quantity shipped (Seddon, 2006a). These losses reduce the quantity of the liquefied energy carriers, which directly affect their economic values. The cost of shipping LNG is (0.5–1.8 $/MMBtu) based on the capital and operational costs of the ship with an assumption of 1% BOG generation (Cho et al., 2018). For instance, Khan (2018) compared energy consumption and GHG emissions from wall to tank of different petroleum and natural gas fuels pathways. The study stated that for fuels produced from natural gas, there are several parameters with high sensitivities, for example, methane leakage, leaks during processing, and CO_2 venting during processing (Khan, 2018). This emphasizes that considering costs related to venting or leaks of produced fuel is significant since these parameters have high sensitivities in natural gas derived fuels. In regard to the economics, BOG studies have been mainly implemented on the LNG reliquefication facility to reduce BOG generation. Kim et al. investigated the economic feasibility of an LNG ship that has a BOG liquefaction facility onboard for a high-pressure fuel supply system. The study aimed to utilize the generated BOG from tanks for fuel production by considering total annual cost as an objective function. The results state that the use of the BOG liquefaction facility on LNG ship reduces the total annual cost by 9.4% compared to the use of high-pressure fuel system when the price of LNG is 5 US $/MMBtu. The study also shows that when the LNG price is lower than 4 US $/MMBtu, BOG liquefaction facility is not economically effective to be used for fuel production compared to the high-pressure fuel supply system (Kim et al., 2019).

Several researchers have proposed various solutions to decrease the cost of BOG generation during transporting the energy of natural gas as LNG. Li et al. proposed to decrease the BOG re-condensation process at LNG arrival terminals by controlling condensing LNG flow that is related to pressure within the re-condenser. This approach decreases the energy consumption for the BOG re-condensation process by 91.2 kW and around 1.3 t/h of BOG is recovered (Li et al., 2012). Romero Gomez et al. proposed a design of the BOG reliquefication facility on LNG ship operating with cascade vapor compression cycle accordingly with the use of refrigerants namely; ethylene and propylene. The analysis reduced the power consumption of the system of about 15% and improved the system exergetic efficiency of 19.35 compared to original design (Romero Gómez et al., 2015). Tan et al. studied the reduction of BOG generation during LNG carriers by using an ejector enhancement system for BOG reliquefication. The system uses two ejectors to reduce energy loss as BOG from the tank and inject some part of fuel BOG into the ship compression system. This method improves the system COP of 28% compared to the existing system and the specific energy consumption of the system is reduced to 0.59 kWh/kg of BOG (Tan et al., 2016). Tan et al. also proposed a new BOG reliquefication system that uses a dual mixed refringent cycle for LNG carriers to improve system efficiency. The power consumption by compressors used to handle the BOG generation is reduced by 25%, and the exergy efficiency and COP of the system are 41.3% and 0.25 respectively. This indicates that employing a dual mixed refringent cycle based BOG reliquefication system can substantially improve the system to reduce the cost of BOG handling (Tan et al., 2018).

Boe et al. presented an economic comparison of three BOG treatment schemes namely; two-stage BOG re-condensation system with the pre-cooling facility, an integration between LNG cold energy generation system and BOG re-condensation system, and combination of BOG fueled gas turbine and cold energy generation system. The present value of these three schemes was investigated based on the interest rate, BOG content, and electricity price. The results showed that when the BOG content increases, the present value of the three schemes increases. When BOG content is 0.15, the present value of the combination of BOG fueled gas turbine and cold energy generation system was 32.3% and 37.9% higher than other systems (Bao et al., 2019). From the literature, the majority of BOG studies that focus on BOG reduction economics are implemented for mainly LNG as energy carrier. These studies are analyzing BOG generations economically by improving reliquefication systems. However, this study proposes to reduce the BOG problem by transporting the energy of natural gas in different liquefied energy carriers. Since BOG is handled differently, this study will treat BOG loss as unit cost. BOG generation is not captured in production and transportation phases and it is flared to the environment so re-liquefaction of boil off gas rate (BOR) is 0. This assumption is made based on the literature. The most common used method for BOG handling is through flaring (Liu et al., 2010). However, there are some industrial applications, which capture and re-liquefy generated BOG. For example, a recovery facility is placed LNG carriers: Q-Flex and Q-Max ships (membrane design). Installation of a re-liquefication facility has high cost associated and due to the system complexity and sensitivity, conventional LNG carriers (mostly sphere designs), do not consist of BOG recovery facility (Anderson et al., 2009; GIIGNL, 2019). In this study, conventional spherical tank carriers are considered and no re-liquefaction facility is implemented, hence generated BOG during voyage is vented to the environment. In this way, we emphasize the avoidable cost once proper handling of BOG is carefully addressed.

Treating generated BOG as the unit price has several advantages. Firstly, knowing the cost of BOG that is generated during the production and transportation of liquefied energy carriers helps in indicating which energy carrier is the most energy-efficient in terms of mass losses. Since the energy carriers have different BOG rates, an energy carrier with low BOG cost is favorable. Moreover, BOG can be handled either by improving tank insulation or by implementing reliquefication facilities to capture the generated BOG. By indicating the cost of produced BOG in various energy carriers, this can help in implementing the most economical solution. Lastly, the cost of BOG elucidates the potentiality of using different energy carriers for large energy transport such as liquid ammonia, DME, methanol, and liquid hydrogen instead of using LNG as a dominating natural gas energy carrier.

Thus, the production cost of liquefied energy carries from natural gas by accounting for generation of BOG during the production phase is calculated. In addition, the transportation cost of transporting the energy of natural gas via LNG, liquid ammonia, methanol, DME, and liquid hydrogen is calculated with accounting BOG generation as a cost within the total transportation cost. Consequently, the main objectives of the study are listed as follows:

- Calculating production and transportation cost of natural gas energy by other potential liquid energy carriers while accounting for BOG generation as an individual cost.

- Estimating the cost breakdown (capital cost, operations costs, and BOG cost) of production and transportation costs of these energy carriers.
- Examining the effects of natural gas cost on the total production cost.
- Determining the transportation cost via various energy carriers per unit volume, mass and energy content.
- Studying the effects of changing ship capacity and transportation distance on transportation cost of natural gas energy.
- Accounting the social cost of CO_2 equivalent GHG emissions associated with the production and transportation of the energy carriers.
- Observing the effects of increasing social cost of carbon on production and transportation phases.

2. Methodology

The raw gas feed is considered to be delivered to the LNG plant, liquid ammonia plant, methanol plant, DME plant, and liquid hydrogen plant in Mesaieed Industrial City (MIC), Qatar, from the North Field. The North Field is a non-associated natural gas zone with recoverable reserves of 900 trillion cubic feet (tcf) located offshore the northeast Qatar peninsula (QatarGas, 2020). A country with large hydrocarbons reserves is usually responsible for exploration, conversion, and transportation of the hydrocarbons to other countries to gain the most economic value of its reserves during the supply chain, which is the case in Qatar. Qatar is a successful example of gaining most of the economic values of its hydrocarbons' reserves. Qatargas is a company owned by the state of Qatar and it owns major phases of the LNG supply chain; the conversion of natural gas into LNG and transportation in forms of LNG (Qatargas, 2018). Therefore, the supply chain of this study covers the conversion of natural gas into liquefied forms and transportation to demanded regions.

The natural gas is converted into LNG, liquid ammonia, methanol, DME, and liquid hydrogen. After conversion, the five energy carriers are transported to energy demanded locations. In this study, cost analysis in the context of conversion of natural gas into liquefied forms and transportation of the energy of natural gas to demanded regions is conducted.

The total production cost of liquefied energy carriers typically covers the investment cost and operations cost of each plant. In this study, the production cost of converting natural gas energy into a liquefied form of energy covers investment cost, operation cost, and BOG cost. The generation of BOG during the production of a liquefied energy carrier is vented to the environment or sent to a reliquefication facility (Moon et al., 2007). Since different methods are used to deal with the BOG and the generated BOG is a significant issue during a liquefied energy carrier supply chain. In this study, the quantity lost as BOG is proposed to be accounted for within the total production cost.

Moreover, the same approach is applied to estimate the total transportation cost. Generally, the generated BOG during ocean transportation is either used as fuel for the ship or rooted reliquefication facility on the ship that is used to liquefy the gas and send it back to storage tanks (Gómez et al., 2013). Since the generated BOG during transporting liquefied energy carriers is utilized in different ways, the lost mass due to BOG is accounted as a cost. Thus, the total transportation cost accumulates of a capital cost of a ship, operations cost, and the generated BOG during ocean transportation. Fig. 1 shows the cost of producing one gigajoule equivalent of energy carriers from natural gas and transporting to demanded regions based on a discounted cash flow analysis. All the costs presented in this study are in U.S dollars.

Table 1
Composition of Qatari LNG (Natural Gas Global, 2015).

Component	Mole %
Nitrogen	0.27
Methane	90.9
Ethane	6.43
Propane	1.66
Butane and higher hydrocarbons	0.74

3. Analysis

3.1. Production cost

To determine the production cost for liquefied energy carriers, all associated costs and plants are accounted for. For a fair comparison, the production statistics of LNG, DME, liquid ammonia, methanol, and liquid hydrogen are taken from real plants located in the same geographical location. These plants convert the energy of natural gas into energy carriers. The composition of LNG is presented in Table 1.

Furthermore, steam methane reforming process is used to produce hydrogen, the Haber–Bosch process is used to produce ammonia, methanol is produced in two step processes: steam reforming of methane followed by synthesis gas conversion into methanol, and DME is also produced in two steps: syngas has to be synthesized first, followed by a direct reaction combining production and dehydration of methanol to produce DME. Since the physical and chemical characteristics of each energy carriers alter, different production costs are expected. Thermophysical properties for the five energy carriers are listed in Table 2.

For example, 50% of the total capital costs of LNG production accounts for gas liquefaction. The rest is composed of (18%) LNG storage, (16%) utilities, (10%) loading facilities, and (6%) gas pretreatment (Aj et al., 1999). Whereas the production costs of liquefied ammonia are strongly dependent on the capital costs and costs of gas usage. Gas usage has been estimated for ammonia production to be about 25 mmBTU/t (Seddon, 2006b). The production costs of liquefied energy carriers mainly consist of costs of used equipment to produce the energy carriers, costs of gas usage, and costs of non-operating gas. In this study, all these costs are accounted for with the addition of generated BOG costs and social cost of carbon to determine the total production costs. The production cost statistics of each liquefied energy carriers are presented in Table 3. The capital costs of different plants with 3 years of construction and 20 years of lifetime are determined based on their capacities. Plant capacity and daily production rates for each plant are obtained from published information (Seddon, 2006b). The capital costs are all the cost associated with utilities, and the investment cost capitalizes the return of investment during construction of a plant. The value for return of capital (ROC) is estimated for 3 year of construction with 5% interest rate. The operations cost consists of fixed operating (Non-gas cost) cost and variable operating cost (gas usage). The fixed operating cost covers working capital, labor, maintenance, administrative costs, catalysts and chemicals costs. The working capital is assumed to be 5% and it is treated as annual operating cost. Whereas labor costs (direct and indirect), maintenance (material and labor), and administrative cost (insurance and local land taxes) are charged each at the rate of 1.5% of the capital per annum. For variable operating cost, since all the plants use natural gas, the purchase of natural gas is the only variable of interest and it is assumed to be 2 \$/GJ in this study for the base case scenario. Later on, the sensitivity analysis considers different prices of natural gas. The costs of gas usage are typical multiplication of the price of gas and the quantity of gas usage for each plant. Moreover, BOG

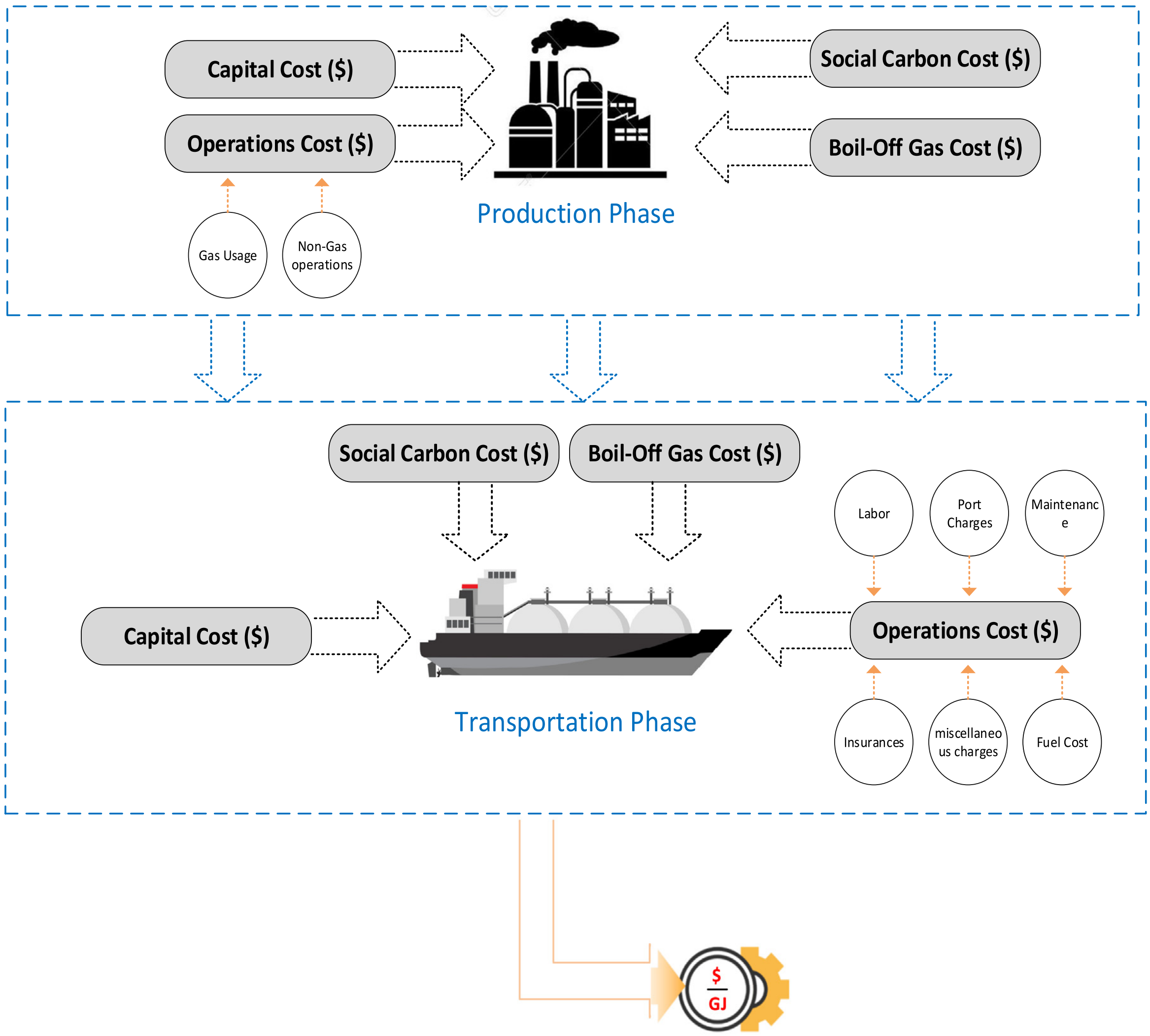


Fig. 1. The involved phases to determine the total cost of a liquefied energy carrier.

Table 2
Significant thermophysical properties of LNG, DME, ammonia, methanol, and hydrogen.
Source: Al-Breiki and Bicer, 2020a, Al-Breiki and Bicer, 2020c, Software F-Chart, 2015.

Thermophysical Properties	LNG	DME	Ammonia	Methanol	Hydrogen
Density (kg/m^3)	423.1	735.5	682.8	805	71.1
LHV (MJ/kg)	48.6	28.9	18.6	19.9	120
Production BOG (%)	0.176	0.024	0.052	0.071	1.189
Transportation BOG (%)	0.12	0.011	0.025	0.0005	0.52

costs are the amount of BOG generated during production from a storage tank and loading facilities. The amount of generated BOG is multiplied by the selling price of the liquefied energy carriers to determine the costs of BOG generation. The summation of investment cost, gas usage cost, and BOG costs estimate the total cost for each energy carrier in production phase as presented in Eq. (1).

$$C_{P_{total\ cost}} = C_{P_{operations}} + C_{P_{investment}} + C_{P_{BOG}} \tag{1}$$

Since the production cost is the ratio between the total costs during production phase and the production capacity, the total production capacity is calculated by the annual production rate and the LHV of the energy carriers. By knowing the total cost and production capacity of the plants, the production cost of each energy carrier is determined in \$/GJ. The production costs of this energy carries are compared with the literature for validation purposes. Besides, providing a cost break-even analysis of the production cost with accounting for investment cost, operations cost, and BOG cost can estimate how much of each contribution of the total cost. This can help in making effective decisions when the BOG problem is tackled.

Since the five liquefied energy carriers are using natural gas as feedstock, any change of natural gas prices affects the production cost directly. Thus, a sensitivity analysis is implemented based on changing the natural gas prices from 1–4 \$/GJ on the production cost for each energy carrier.

3.2. Transportation cost

Capital cost of a shipping tanker, and ship operations costs, and energy losses (BOG generation) are accumulated together to estimate the transportation of each energy carrier from a supplied region to a demanded region. The capital costs for each ship used to carry LNG, liquid ammonia, methanol, liquid hydrogen, and

Table 3
Production cost statistics for each liquefied energy carrier.
Source: Seddon, 2006b.

	Unit	LNG	Ammonia	Methanol	DME	Hydrogen
Plant capacity						
Production[a]	kg/a	9,000,000,000	1,275,000,000	1,275,000,000	915,000,000	450,000,000
Production	kg/day	25,714,286	3,642,857	3,642,857	2,614,286	1,285,714
Capital cost						
Capital cost (Seddon, 2006b)	MM$	5,225	605	378	390	378
Return on capital[b]	%	14.6	14.6	14.6	14.6	14.6
Investment cost	MM$	762	88	55	57	55
Operations cost						
Non-gas cost (Seddon, 2006b)	MM$	1,018	165	91	104	88
Gas usage (Seddon, 2006b)	GJ/y	388,000,000	29,620,000	32,200,000	32,610,000	68,000,000
Cost of gas	$/GJ	2	2	2	2	2
Usage gas cost	MM$	776	59	64	65	136
BOG cost						
BOG from storage/loading	kg	15,813,000	663,000	310,080	649,650	5,350,500
Market price[c]	$/GJ	5.93 (Dahl, 2006)	28.2 (Schnitkey, 2018)	16.3 (Methanex, 2015)	15.06 (CEIC, 2018)	12 (ACIL Allen Consulting)
BOG cost	$	4,557,275	908,654.76	103,665.95	282,749.77	7,704,720
Total costs	**MM$**	**2,562**	**314**	**211**	**226**	**287**
Available Energy	**GJ**	**437,400,000**	**23,715,000**	**25,372,500**	**26,443,500**	**54,000,000**

[a]This represents the production for 350 days in a year.
[b]The discounted cash flow (DCF) rate of 10% for 3 years constructing duration and a plant lifetime of 20 years generates a return on capital investment of 14.6%.
[c]Selling price for each commodity in the year of 2020.

Table 4
The capital cost of LNG, liquid ammonia, methanol, DME, and liquid hydrogen ship in ($/m^3).

Energy Carrier	Tanker Cost ($/m^3)	Reference
LNG	1200	Kamalinejad et al., 2016, Seddon, 2006a
Liquid Ammonia	1016	Morgan (2013)
Methanol	750	Magraw, 2017, Seddon, 2006a
DME	750	Magraw, 2017, Seddon, 2006a
Liquid Hydrogen	1355	Morgan (2013)

DME are estimated in $/m^3 as listed in Table 4. By knowing the tanker cost in $/m^3, the total capital cost of a liquefied energy tanker can be estimated. This approach is used for the five energy carriers to estimate the capital cost of different tankers.

The ship tankers vary in cost due to different thermophysical properties of the carried energy. For example, the storage temperature for LNG is −162 °C so the cost of used materials to keep the LNG temperature is high due to required high insulation materials. For a fair comparison, the five shipping tankers have the same capacity of 160,000 m^3. The carried amount of each energy carrier is calculated based on the density while the carried energy is estimated by LHV. The capital costs, operations costs, and BOG cost parameters are shown in Table 5.

The capital costs for the same ship capacity with 15 years lifespan and 10% discount factor are estimated based on the cost of the tank per metric cube. The operations cost of a shipping tanker consists of labor costs, ports charges, maintenance, insurances, and miscellaneous charges as shown in Eq. (2).

$$\sum C_{operations} = C_{labor} + C_{port_{charges}} + C_{maintenance} + C_{insurance} + C_{miscellaneous} \quad (2)$$

Moreover, heavy fuel oil (HFO) is used to fuel the ship and the cost of the total required HFO is added to the operations costs. To generate 100 kWh of energy, vessel running on HFO shall consume about 9.234 kg (9.419 L) of fuel. The average power required by the engine of 160,000 m^3 capacity is 31,400 kW. Therefore, the fuel needed to carry the full capacity is 2899 kg of HFO (Engines, 2013; Sharples, 2019). Operations costs differ from each energy carrier due to the required fuel which is dependent on the carrier capacity. Each energy carrier has a different daily BOG rate therefore the quantity of lost mass differs. The BOG cost is the total loss amount of liquefied energy carriers during the voyage duration. The cost of generated BOG is calculated by multiplying the selling price and the mass of each energy carrier. The summation of investment cost, operations cost, and BOG costs estimate the total cost (before social cost of carbon) for each energy carrier in transportation phase as presented in Eq. (3).

$$C_{T_{total\ cost}} = C_{T_{operations}} + C_{T_{investment}} + C_{T_{BOG}} \quad (3)$$

The ratio of the total cost and the quantity shipped estimate the total transportation cost for each energy carrier in $/GJ. Knowing the transportation cost of the energy carriers in different units such as $/kg can enhance the comparison analysis, the transportation cost of the energy carriers is estimated in unit mass. This can be implemented by multiplying the transportation cost of the energy carriers by their densities. Moreover, the cost break-even of the transportation cost contributors is shown for the purpose of providing a better understanding of how BOG is significant when liquefied energy is transported.

Moreover, a sensitivity analysis is implemented on ship capacity and distance parameter. Changing the ship capacity parameter for each energy carriers from 100,000 m^3 to 160,000 and to 250,000 for studying the impact on total transportation costs. Transporting the energy carriers to three different locations is considered based on distance. Since the energy of natural gas is transported to three different locations, the total cost of transportation is varied because of the transportation distance. The distances to transport the five energy carriers form Qatar to Japan, to India, and to China are 12,000 km, 2400 km, and 9700 km respectively (PortWorld, 2012).

In addition, since this study assumes that generated BOG is not captured and it is flared to the environment, considering environmental cost associated with producing and transporting energy carriers can illustrate which of these energy carriers are lower cost if environmental costs are included within the total

Table 5
Cost parameters for ocean transportation of LNG, ammonia, methanol, DME, and hydrogen from Qatar to Japan.
Source: Seddon (2006b).

	Unit	LNG	Ammonia	Methanol	DME	Hydrogen
Ship capacity	m^3	160,000	160,000	160,000	160,000	160,000
Capacity	kg	67,696,000	109,248,000	128,800,000	117,680,000	11,376,000
Logistics						
From Qatar to Japan						
Distance (PortWorld, 2012)	km	12,000	12,000	12,000	12,000	12,000
Sailing time[a]	day	13	13	13	13	13
Trips/year[b]		24.14	24.14	24.14	24.14	24.14
Sailing days/year	day	313.79	313.79	313.79	313.79	313.79
Capital cost						
Capital cost (Seddon, 2006b)	MM$	192	162	120	120	216
ROC[c]	%	15.19	15.19	15.19	15.19	15.19
Investment costs	MM$	29	24	18	18	32
Operations cost						
Labor	MM$	2.5	2.5	2.5	2.5	2.5
Required fuel	kg	7,327,540	11,825,205	13,941,549	12,737,900	1,231,359
Fuel cost[d,e]	MM$	4.2	6.8	8	7.3	0.7
Port charges	MM$	3.6	3.6	3.6	3.6	3.6
Maintenance (4% Capex)	MM$	7.6	6.5	4.8	4.8	8.6
Insurance (15% Opex)	MM$	2.7	2.9	2.8	2.7	2.3
Misc (10% Opex)	MM$	1.8	1.9	1.9	1.8	1.5
Total operating Cost	MM$	22.5	24.3	23.4	22.9	19.3
BOG cost						
BOG during transportation	kg	25,491,045	8,570,317	202,082	6,277,619	37,838,929
Market price	$/GJ	5.93 (Bluegold Research, 2020)	28.2 (Schnitkey, 2018)	16.3 (Methanex, 2015)	15.06 (CEIC, 2018)	12 (ACIL Allen Consulting)
Cost of BOG	MM$	7.3	4.5	0.67	2.7	54
Delivered quantity	kg	1,634,041,379	2,637,020,689	3,108,965,517	2,840,551,724	274,593,103
delivered energy	GJ	79,414,411	49,048,584,827	61,868,413,793	82,091,944,827	32,951,172,413

[a]The ship operates for 350 days annually with a speed of 20 (knots).
[b]This consists of sailing time and 36 h turnaround for each trip.
[c]The discounted cash flow (DCF) rate of 10% for a lifetime of 15 years.
[d]Fuel needed to carry the full capacity is 2899 kg of HFO (Engines, 2013; Sharples, 2019).
[e]Cost of HFO is 0.58 ($/kg) (Singapore Bunker Prices, 2020).

Table 6
Global warming potentials (GWP_{100}) of energy carriers in the atmosphere and GHG emissions linked to production of energy carriers.

	GWP_{100} in the atmosphere due to BOG and leaks (kg CO_2 eq./kg fuel)	Reference	GHG in production phase (kg CO_2 eq./kg fuel) (Al-Breiki and Bicer, 2020b)
LNG	21	(Semelsberger et al., 2006)	0.5
Ammonia	0	(Apostol et al., 2008)	2.42
Methanol	2.97	(Kajaste et al., 2018)	0.4
DME	0.3	(Kim, 2016)	0.61
Hydrogen	0	(Filippone, 2014)	14.37

cost. Environmental costs are usually associated with greenhouse gas emissions (GHG). GHG emissions is a measure of pollution that impacts climate change and main gases are carbon dioxide, methane, nitrous oxide, ozone, water vapor, and chlorofluorocarbons. CO_2 equivalent is the measure unit and it represents contribution of each GHG relative to CO_2 to global warming. The used method to manage emissions is social cost of carbon (SCC). This method estimates economic damages associated with increase of emissions in CO_2 equivalent in a given year. These economic damages are related to human health, agricultural needs, and destruction (Social Cost of Carbon, 2016; Niemi, 2017). Therefore, including environmental cost into the total cost of production and transportation, production cost and transportation cost of each energy carrier is presented in Eq. (4) Eq. (5), respectively.

$$\sum C_{P_{total\ cost}} = C_{P_{operations}} + C_{P_{investment}} + C_{P_{BOG}} + C_{P_{enviromental}} \tag{4}$$

$$\sum C_{Total_{cost_{transportation}}} = C_{T_{operations}} + C_{T_{investment}} + C_{T_{BOG}} + C_{T_{enviromental}} \tag{5}$$

where ($C_{environmental}$) represents associated costs with GHG emissions related to producing and transporting the energy carriers and emissions due to BOG. Emissions released associated with producing LNG, liquid ammonia, methanol, DME, and liquid hydrogen are summarized in Table 6. Since all the carriers are assumed to be transported via an ocean tanker fueled by HFO, generated emissions due to power requirements and used raw materials for 1 kg of liquefied energy carrier is 0.08 CO_2 eq. Moreover, emissions associated with generation of BOG are estimated by global warming potential (GWP) of each carrier. The GWP values for the energy carriers are presented in Table 6. DME has a lower GWP100 value than methanol because of its short atmospheric lifetime and a lack of significant absorption features (Good et al., 1998). The environmental cost based on SCC of various energy carriers produced from natural gas is $46. Multiplication of SCC cost with generated emissions equivalent to CO_2 estimate environmental cost for each energy carrier.

Table 7
Calculated total production cost of various energy carriers per unit energy in comparison with the literature.

	This Study $/GJ	Literature (Seddon, 2006a) $/GJ
LNG	5.86	5.76
Liquid Ammonia	13.25	12.90
Methanol	8.33	9.05
DME	8.57	9.52
Liquid Hydrogen	5.32	5.00

4. Results and Discussion

The production costs for LNG, liquid ammonia, methanol, DME, and liquid hydrogen are calculated by the addition of capital cost, operations cost, and the BOG costs. Synthesizing the five energy carriers from natural gas consumes at least 80% or higher of gas energy in their process as presented in Table 3. By comparison, numerous studies propose to produce such commodities from other sources such as electrolysis, biomass and other. However, the production efficiencies of these processes are currently lower compared to natural gas (Eveloy and Gebreegziabher, 2018; Xu et al., 2019). However. they have a great improvement potential as well.

Since, natural gas is considered cost-effective primary source for the production of such commodities, Table 7 shows the total production cost for the energy carriers from natural gas only.

The production cost of this study is higher for the energy carriers compared to literature because of accounting BOG costs within the total production cost. LNG and liquid hydrogen have the lost production cost whereas liquid ammonia has the highest in term of $/GJ. To produce LNG from natural gas, the only requirement is the gas pretreatment and liquefaction process. Methanol and DME have higher production costs from LNG and hydrogen but lower cost compared to ammonia. The presence of extra processes such as reformers and synthesis reactors increase production costs. Since DME and methanol boiling temperatures are −24 °C and 64 °C, such property favors in terms of reducing the production cost compared to ammonia, which has a boiling temperature of −34 °C. In addition to the total production cost for the energy carriers, Fig. 2 presents a cost breakdown for capital cost, operations cost, and BOG cost.

The production cost for the energy carriers consists of four main elements; investment cost, gas usage cost, non-gas operations cost, and BOG cost. LNG has almost an equal share of cost between investment cost and gas usage cost of around 30% each. BOG represents 0.18% of the total production cost. Thus, utilizing the generated BOG during the production phase is essential. For ammonia, the non-operation cost represents around 52.70% of the total cost whereas other costs represent about 47.3%. This is due to the need for nitrogen to synthesize ammonia. Methanol and DME have similar cost production structures with a higher percentage of non-gas operations cost compared to other cost factors. BOG cost in hydrogen production accounts for 2.68% which is the highest among the energy carriers. The usage of gas in hydrogen cost production is responsible for 47.30%. This ensures that producing hydrogen via other feedstocks can be alternative in terms of cost reduction.

Since the cost of natural gas plays a significant role in the production of the energy carriers, a sensitivity analysis has been implemented to examine the effect of gas costs on total production cost of various energy carriers as shown in Fig. 3. The cost of natural gas changes from 1 to 4 $/GJ. As the cost of natural gas increases, the production cost of the five energy carriers increases. When the cost of gas increases to 4 $/GJ, the production cost of ammonia becomes 16 $/GJ which is the highest among the energy carriers. Ideally, a country with a large proven reserve would have a low production cost. Thus, converting natural gas into methanol and DME when the production cost of gas is 1 $/GJ cost 7.06 $/GJ and 7.34 $/GJ respectively. By comparison, the production cost of LNG is 7.64 $/GJ when the cost of gas is 4 $/GJ. Therefore, exporting natural gas as methanol and DME is more economically effective specifically for countries with low natural gas production costs compared to countries exporting LNG with high production costs. Moreover, as the cost of natural gas reduces to 1 $/GJ, the production cost of hydrogen becomes around 4.0 $/GJ. This makes producing hydrogen from methane resistance in the market since different proposed processes such as electrolysis require a higher cost.

Moreover, since the BOG rate in transportation phase of LNG is about 0.12%, this value can significantly affect the transportation cost as BOG treated as unit cost. In this study, the cost of generated BOG is calculated based on the current market price of LNG and the generated amount of BOG in transportation phase. The average global price of LNG is around 5.93 $/GJ (Bluegold Research, 2020). Since the price of LNG is changing and future price cannot be predicted, a sensitivity analysis on transportation cost of LNG as market price of LNG varying is presented in Fig. 4. When the market price of LNG is at 1.5 $/GJ, the transportation cost of LNG is at 0.67 $/GJ. As the LNG price reach 11.5 $/GJ, transporting of LNG costs around 0.83 $/GJ, which means increment of price by 24%.

The ocean transport cost for LNG, liquid ammonia, methanol, DME, and liquid hydrogen are calculated based on the addition of capital cost, operations cost and BOG cost. The capital cost for LNG tanker is 15% and 40% higher than ammonia and methanol tankers respectively due to their thermophysical properties of having very low storage temperature which requires high cost insulation materials. This is the case for liquid hydrogen tanker, the capital cost for 160,000 m^3 capacity ship is $216,784,000. By contrast, the capital cost for DME and methanol tankers are typically lower due to the capability of storing in liquid forms near ambient temperature.

Ammonia has the highest tanker operations cost among the energy carriers. The tanker operations cost of liquid ammonia is 8% and 20% higher than LNG and hydrogen, respectively. The reason for high tanker operations costs for ammonia is that the capacity of energy carriers is higher which is impacted by the density of ammonia. Moreover, the BOG rate during ocean transportation of LNG is 0.12% which results in 1,000,000 kg loss of LNG per trip. LNG losses need to be addressed properly either by implementing the BOG facility on board, substituting LNG with different liquefied energy, or improving the quality of shipping tanks. Even though BOG losses reduce the quantity of LNG shipped, LNG still delivers more energy compared to liquid ammonia, methanol, and hydrogen due to its high energy content (heating value). DME has the lowest total transportation cost with almost 15% lower than LNG. Fig. 5 shows the breakdown of the total transportation cost of various energy carriers in $/GJ. The total transportation cost of liquid ammonia is 1.08 $/GJ. The transportation cost of ammonia is the summation of 45.6% of tanker operations cost, 45.9% of tanker capital cost, and 8.5% BOG cost. Transporting the cost of energy as liquid ammonia is higher than LNG in terms of $/GJ because of the lower energy density of ammonia compared to LNG. On the other hand, Fig. 6 shows the total cost of transporting natural gas as LNG, liquid ammonia, methanol, and DME in terms of cost per unit mass. The total transportation cost of liquid ammonia is 0.02 $/kg and 0.038 $/kg is the transportation cost of LNG. Ammonia has a lower cost per unit mass compared to LNG. The energy density of methanol is 22 MJ/kg, which is lower than liquid ammonia 22.5 MJ/kg and

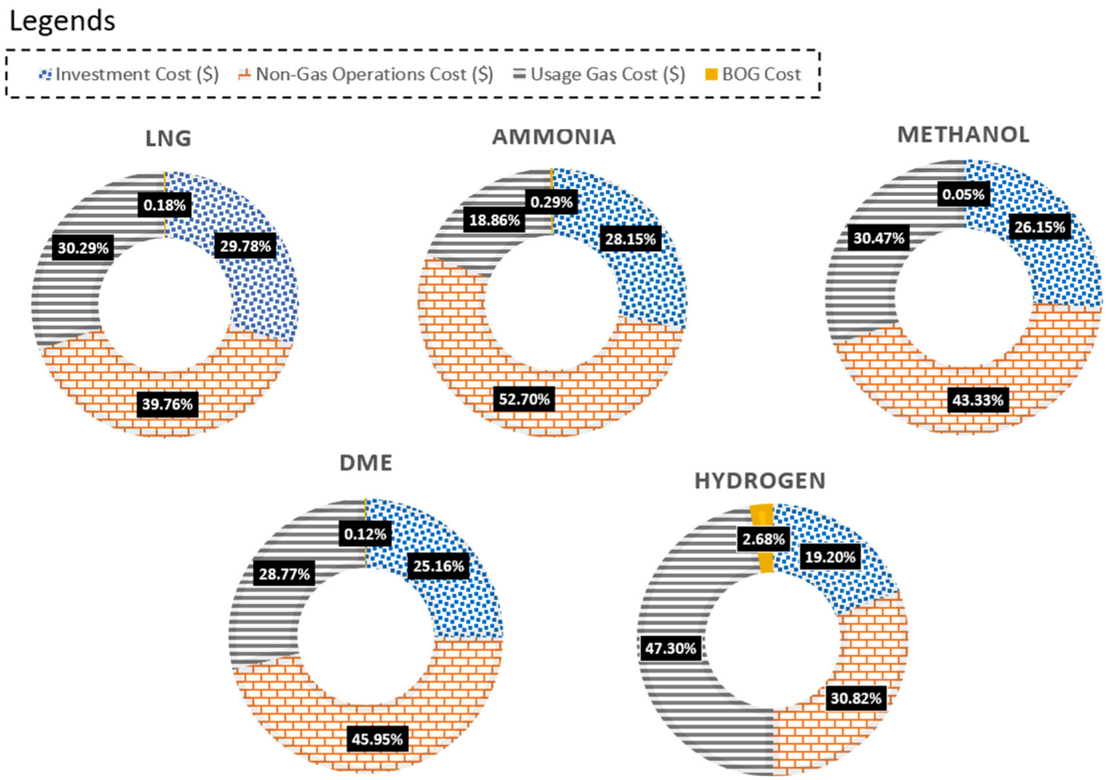


Fig. 2. Cost breakdown of *producing* various energy carriers.

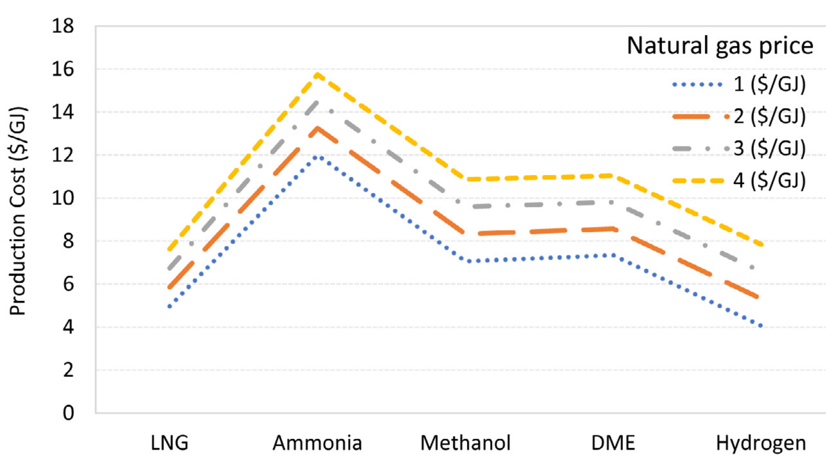


Fig. 3. Effects of changing the cost of natural gas on the total production cost of energy carriers.

LNG 54 MJ/kg; methanol has energy transport cost (in terms $/kg) of about 50% and 15% less than LNG and liquid ammonia, respectively.

Moreover, the total transport costs of LNG, liquid ammonia, methanol, DME and liquid hydrogen in $/m^3 are shown in Table 8. This shows that as the density of the energy carriers increase as the cost in term of cubic meter decreases. For example, methanol has the highest density of 805 kg/m^3. This results in making the cost of transporting energy in the form of methanol are the lowest cost option of about 10.89 $/m^3. In contrast, liquid hydrogen has 60 higher transportation cost compared to methanol. Therefore, methanol is more economically effective when transporting energy in large quantities in terms of cost per meter cubic.

Fig. 7 represents the effects of changing the ship capacity over ocean transportation costs for the energy carriers. Typically, as the ship capacity increases, the transportation cost of the energy carriers decreases. For example, the transportation cost of energy as LNG reduces of about 12.5% when the ship capacity changes from 100,000 m^3 to 260,000 m^3. The total transportation cost of LNG for 250,000 m^3 is 0.7 $/GJ whereas the transportation cost of methanol and DME is 0.63 $/GJ and 0.5 $/GJ, respectively. The cost of LNG is higher because of the BOG generation. Increasing ship capacity increases tanker size, which results in greater surface areas. As the surface area increases, the BOG rates increase. Therefore, due to high BOG rates, while transporting energy as LNG, the cost of transporting LNG is higher compared to DME and methanol. DME and methanol can be more economically effective and lower cost compared to LNG to transport the energy of natural gas for the same ship capacity.

Fig. 8 shows the total transportation of natural gas energy from large natural gas reserve countries to demanded energy regions; India, China, and Japan. The energy of natural gas is

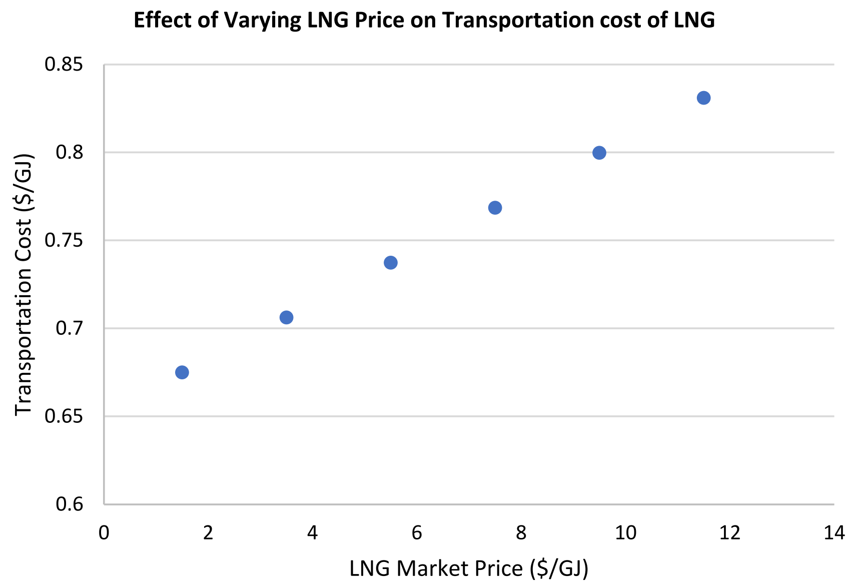


Fig. 4. Sensitivity analysis on transportation cost of LNG as market price of LNG is varying from (1.5 to 12 $/GJ).

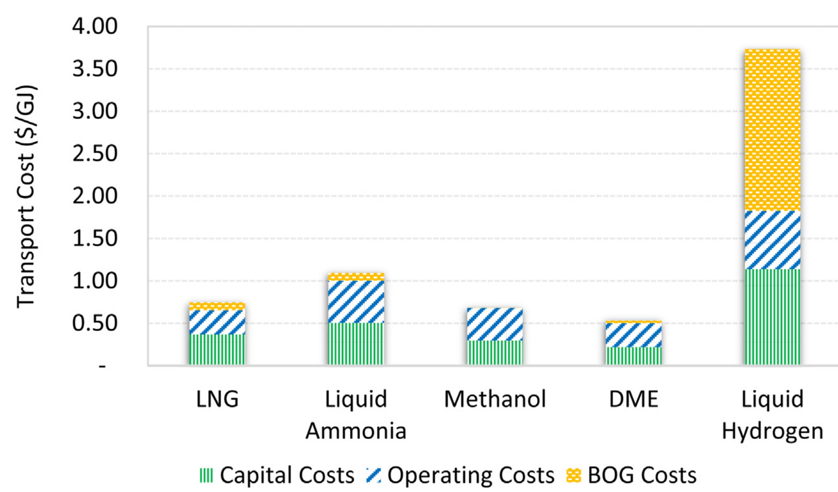


Fig. 5. Breakdown of *total transportation costs* of LNG, liquid ammonia, methanol, and DME in $/GJ.

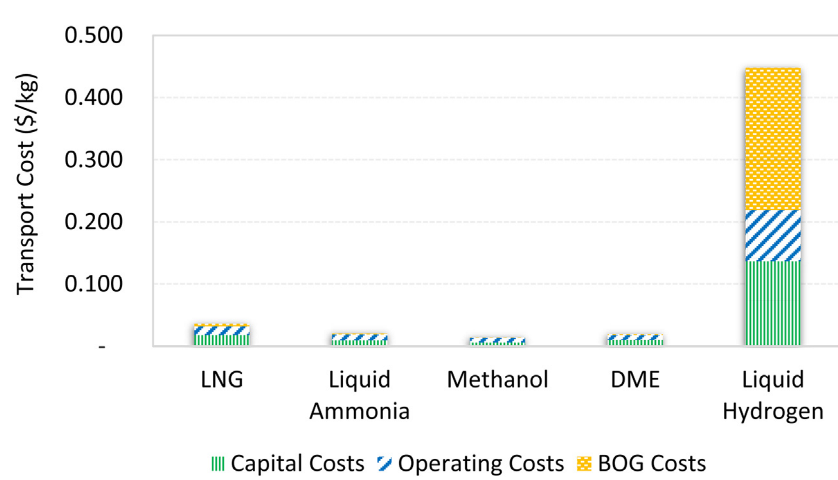


Fig. 6. Breakdown of *total transportation costs* of LNG, liquid ammonia, methanol, and DME in $/kg.

transported from Qatar to these three locations which vary in distance. As the distance increases, the transportation energy costs increase but with varying rates. The distance from Qatar to India is the shortest. Thus, the cost of transporting energy

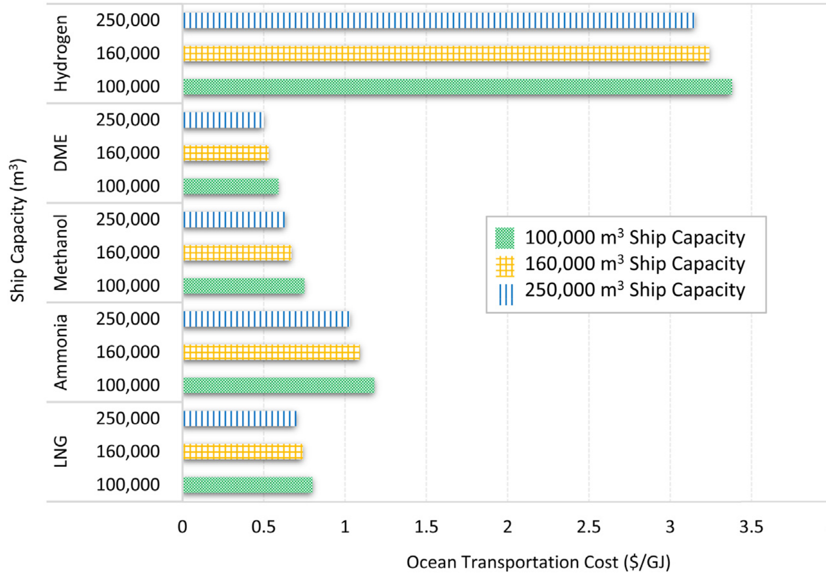


Fig. 7. Sensitivity analysis on ocean transportation cost for various energy carriers based on ship capacity.

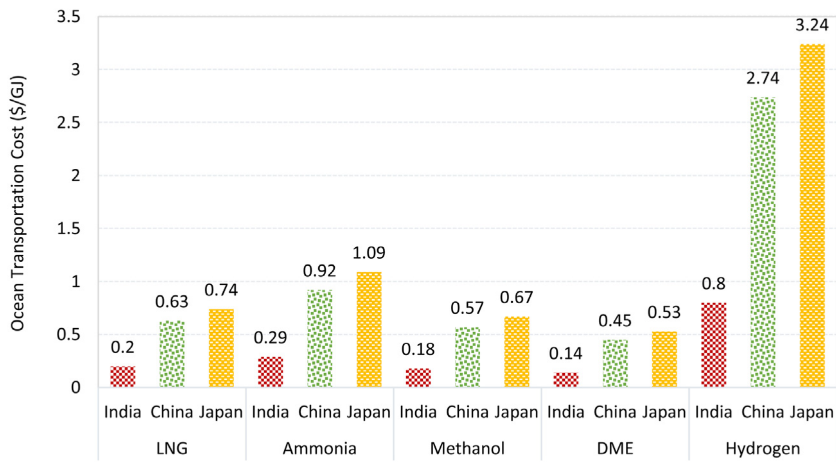
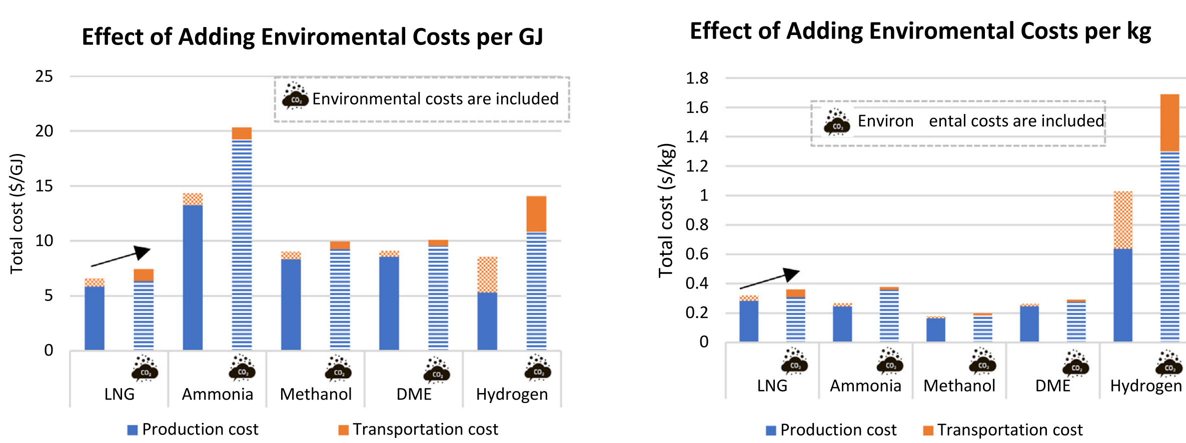


Fig. 8. Costs for transporting natural gas energy via various energy carriers from Qatar to India, China, and Japan.



(a) ($/GJ) **(b)** ($/kg)

Fig. 9. Effect of adding environmental cost (0.137 $/kg CO_2 eq.) within the total cost of various energy carriers per (a) GJ and (b) per kg.

Table 8
Ocean transportation cost of various energy carriers in $/m^3.

	LNG	Ammonia	Methanol	DME	Hydrogen
Cost of ocean transportation ($/m^3)	15.3	13.87	10.89	11.36	27.66

Table 9
Sensitivity analysis on production and transportation costs of various energy carriers at various SCC rates.

Discount Rate	SCC not included		5% 50th Percentile		3% 50th Percentile		3% 95th Percentile	
Social Cost of Carbon (SCC) ($/t CO_2 eq.)	–		13		46		137	
Phase	Production ($/GJ)	Transportation ($/GJ)	Production	Transportation	Production	Transportation	Production	Transportation
LNG	**5.86**	**0.74**	↑2%	↑12%	↑9%	↑43%	↑26%	↑127%
Ammonia	**13.25**	**1.09**	↑13%	↑0.2%	↑45%	↑0.8%	↑135%	↑2%
Methanol	**8.33**	**0.68**	↑3%	↑0.3%	↑11%	↑1.2%	↑33%	↑4%
DME	**8.57**	**0.53**	↑3%	↑0.3%	↑11%	↑1.2%	↑34%	↑4%
Hydrogen	**5.32**	**3.24**	↑29%	↑0.0%	↑103%	↑0.0%	↑308%	↑0.1%

is lower compared to large distance transportation. The cost of transporting the energy from natural gas via liquid hydrogen from Qatar to India is 0.8 $/GJ and the cost to transport LNG from Qatar to Japan is 0.74 $/GJ. This indicates that hydrogen can be cost-effective to be transported for a short distance. A country with rich gas reserves can also start transporting the energy of some of its gas via DME and methanol. The transportation costs of DME and methanol from Qatar to China are 0.45 $/GJ and 0.57 $/GJ, respectively. These costs are 25% and 10% lower compared to transporting natural gas energy as LNG to the same distance with the same ship capacity of 160,000 m^3. Furthermore, the cost of transporting energy of natural gas as liquid ammonia from Qatar to India is 53% cheaper than transporting the energy as LNG from Qatar to China. Since both liquid hydrogen and liquid ammonia are carbon-free and have no direct greenhouse gas (GHG) effect, converting the energy of natural gas into these commodities can enhance the country's economy by diversifying its exports in the energy sector.

In addition, addressing the environmental cost associated with producing and transporting the energy carriers can provide a clearer picture of which of these carriers meet the environmental regulations set by IMO (DNV GL, 2019). Fig. 9 illustrates the effects of adding the environmental costs in terms of CO_2 equivalent emission of GHG associated with the production and transportation of the energy carriers, where Fig. 9(a) presents the total cost per GJ and Fig. 9(b) per kg. For LNG, adding environmental cost of 0.137 $/kg CO_2 eq. into production cost and transportation cost results in increasing the cost by 9% and 43%, respectively. The transportation cost increment (when environmental cost is added) is found to be the highest among the energy carriers. This is due to released methane as BOG to the environment. On the other hand, adding environmental cost within the transportation cost of liquid hydrogen and liquid ammonia results in increment of about 0.04% and 0.75%, respectively caused by the HFO burning of the ocean tanker. It is noted that GWP of these fuels is zero when released to environment as given in Table 6. Consequently, considering the transportation phase only, transporting the energy of natural gas via liquid ammonia and liquid hydrogen are economically beneficial compared to LNG transport when the social cost of carbon is accounted for. However, producing liquid ammonia and liquid hydrogen from natural gas releases significant emissions, hence when the environmental costs are included during the production, they do not become as economically favored. This is due to rising production price of about 45% in liquid ammonia and 103% in liquid hydrogen. These raises are obtained because of unused and uncaptured carbon dioxide during reforming reactions. For instance, production of one ton of hydrogen via reforming of natural gas results in producing 9 to 12 of CO_2 eq. (Collodi, 2010). However, when the SCC price is higher, ammonia can become feasible as well that is demonstrated in the sensitivity analysis in Table 9.

Since SCC is the used methodology to estimate the environmental cost, SCC involves estimating damages caused by the aggregate accumulation of the emissions. Such analysis goes far into the future. Hence, the computed SCC might be an underestimation of damages and the net present value (NPV) of damage estimates, which is sensitive to the discount rate, is used to estimate environmental emissions. Therefore, Table 9 presents sensitivity analysis on production and transportation costs of various energy carriers at different SCC prices. In Table 9, columns 3 and 4 contains the average value (50 percentile) and column 5 has the (95 percentile), which presents damage estimation associated with extreme climate outcomes. The discount rate of 3% with average value of 50 percentile is widely used as an appropriate for NPV estimation of SCC. As the SCC increases, the transportation cost of LNG increases dramatically. This increment favors liquid ammonia as an energy carrier of natural gas. When SCC cost is at 137 $/t CO_2 eq., the transportation cost of liquid ammonia is 1.11 $/GJ, whereas LNG transportation cost becomes 1.68 $/GJ. In addition, the production and transportation costs of DME and methanol are not facing rapid increment in their costs as SCC included within their production and transportation cost compared to LNG, liquid ammonia, and liquid hydrogen. This is due to usage of carbon in their chemical reaction in the production phase and lower BOG rate in transportation phase.

5. Conclusions

Cost estimation of producing and transporting the energy of natural gas via LNG, liquid ammonia, methanol, DME, and liquid hydrogen is implemented. In this study, production and transportation costs of the five energy carriers consist of: (1) investment cost, (2) operation cost, and (3) BOG cost. The reason of including BOG cost within the total cost is that the generated BOG during the supply chain of a liquefied energy carrier is treated differently by flaring out to the environment or capturing it for different purposes such as power requirements or reliquefication. Therefore, BOG is treated as unit cost and the social cost of carbon (SCC) is also included within the total cost. The main findings of this study are presented as follows:

- The production cost of LNG, liquid ammonia, methanol, DME, and liquid hydrogen from natural gas is calculated as 5.86 $/GJ, 13.25 $/GJ, 8.33 $/GJ, 8.57 $/GJ, and 5.32 $/GJ, respectively. BOG represents 0.18% of the total LNG production cost whereas BOG generated during methanol production accounts for 0.05% of methanol production cost. Thus, utilizing the generated BOG during the LNG production phase is essential. Additionally, converting natural gas energy into methanol cost is about 7.34 $/GJ (when the cost of natural gas is 1 $/GJ). On the other hand, the production cost of LNG is 7.64 $/GJ when the cost of gas is 4 $/GJ. Therefore, exporting natural gas energy as methanol is more economically effective specifically for countries with low natural gas production costs compared to countries exporting LNG with high production costs.

- For the transportation phase of the energy carriers, the capital cost for LNG tanker is 15% and 40% higher than ammonia and methanol tankers respectively due to their thermophysical properties of having lower storage temperatures, which require higher cost of insulation materials. Moreover, the daily BOG rate during ocean transportation phase of LNG is 0.12%, which results in 1,000,000 kg loss of LNG per trip (for 12,000 km distance that is 13 sailing days) for a tanker capacity of 160,000 m^3. The total transportation costs of LNG and liquid ammonia are calculated 0.038 $/kg and 0.02 $/kg, respectively. Ammonia has a lower cost per unit mass (kg) compared to LNG. Nevertheless, per unit energy (GJ), LNG transportation cost is lower due to greater heating value of LNG when SCC is not accounted for. However, when high SCC is included, the final results vary and transform into the favor of ammonia. In addition, the lower heating value of methanol is 19.9 MJ/kg, which is lower than LNG (48.6 MJ/kg), methanol has energy transport cost of about 50% of LNG in terms $/kg.
- As the ship capacity increases from 100,000 m^3 to 260,000 m^3, the transportation cost of LNG reduces about 12.5%. This due to low density of LNG, which allows carrying more quantity over unit volume. As the transported quantities increase, the transported cost decreases over the same volume. The transportation cost of LNG for 250,000 m^3 is 0.7 $/GJ whereas the transportation costs of methanol and DME are 0.63 $/GJ and 0.5 $/GJ, respectively. The cost of LNG is higher due to the BOG generation. DME and methanol can be more economic compared to LNG to transport the energy of natural gas for the same ship capacity.
- As the distance between energy importer countries and exporter countries decreases, as expected, the transportation cost decreases. The cost of transporting the energy of natural gas via liquid hydrogen from Qatar to India is found to be 0.8 $/GJ and the cost to transport LNG from Qatar to Japan is 0.74 $/GJ. This indicates that hydrogen can be cost-effective to be transported for short distances unless improvements happen, which decreases the generated BOG during the liquefied hydrogen supply chain. For example, a country with rich gas reserves can also start producing and transporting the energy of natural gas via DME and methanol. The transportation costs of DME and methanol from Qatar to China are 0.45 $/GJ and 0.57 $/GJ, accordingly. These costs are 25% and 10% lower compared to transporting natural gas energy as LNG to the same distance with the same ship capacity of 160,000 m^3.
- The cost of transporting energy of natural gas as liquid ammonia from Qatar to India is 53% cheaper than transporting the energy as LNG from Qatar to China. For rich natural gas energy resource country such as Qatar, transporting DME and methanol in large quantities can become more economically effective compared to LNG when the necessary actions are taken. As well as converting the energy of natural gas into liquid hydrogen and liquid ammonia (carbon-free and no direct greenhouse gas effect) for short distances transport can enhance the country's economy by diversifying its exports in the energy sector.
- For LNG, including the SCC (at 46 $/t CO_2 eq.) in the production and transportation cost results in increasing of the total cost by 9% and 43%, respectively. Whereas the total cost increases by 0.04% in liquid hydrogen and 0.75% in liquid ammonia as environmental cost associated with CO_2 equivalent is added into the total cost in transportation phase. Hence transporting the energy of natural gas via liquid ammonia and liquid hydrogen can become economically favorable compared to LNG transport.
- As the social cost of carbon increases to 137 $/t CO_2 eq., the total transportation cost of LNG increases dramatically. LNG, liquid ammonia, methanol, and DME transportation cost become 1.68 $/GJ, 1.11 $/GJ, 0.70 $/GJ, 0.55 $/GJ. This increment favors liquid ammonia, methanol and DME as an energy carrier of natural gas. However, liquid hydrogen transportation cost (3.24 $/GJ) is still the highest even though the increment of the cost is about 0.1% when SCC is included within the transportation cost.

Nomenclature

BOG	Boil-off gas
CIS	Commonwealth of Independent States
C_P	Production cost
C_T	Transportation cost
DME	Dimethyl Ether
GTL	Gas-to-liquid
GHG	Green House Gas
HFO	Havey Fuel Oil
ICS	International Chamber of Shipping
MIC	Mesaieed Industrial City
MM$	Million US dollar
IMO	International Maritime Organization
LPG	LPG liquid petroleum gas
LNG	Liquefied natural gas
LHV	Lower heating value
MJ	Megajoule
MT	Million Ton
NPV	Net present value
SCC	Social cost of carbon
TCF	Trillion cubic feet
U	Overall heat transfer coefficient for the tank (W/m^2 K)

CRediT authorship contribution statement

Mohammed Al-Breiki: Formal analysis, Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing - original draft, Methodology, Software, Investigation. **Yusuf Bicer:** Supervision, Conceptualization, Methodology, Project administration, Writing - review & editing, Resources.

Declaration of competing interest

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

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References

ACIL Allen Consulting, 2018. Opportunities for Australia from Hydrogen Exports. Melbourne.

Aj, F., Gl, J., Tr, T., 1999. Developments in natural gas liquefaction. Hydrocarb. Process. 78, 47–56.

Al-Breiki, M., Bicer, Y., 2020a. Investigating the technical feasibility of various energy carriers for alternative and sustainable overseas energy transport scenarios. Energy Convers. Manag. 209, 112652. http://dx.doi.org/10.1016/j.enconman.2020.112652.

Al-Breiki, M., Bicer, Y., 2020b. Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization. Journal of Cleaner Production Submitted for publication.

Al-Breiki, M., Bicer, Y., 2020c. Technical assessment of liquefied natural gas, ammonia and methanol for overseas energy transport based on energy and exergy analyses. Int. J. Hydrog. Energy http://dx.doi.org/10.1016/j.ijhydene.2020.04.181, In press.

Anderson, T.N., Ehrhardt, M.E., Foglesong, R.E., Bolton, T., Jones, D., Richardson, A., 2009. Shipboard reliquefaction for large LNG carriers. In: Proc. 1st Annu. Gas Process. Symp.. Elsevier, pp. 317–324. http://dx.doi.org/10.1016/B978-0-444-53292-3.50039-0.

Apostol, V., Popescu, G., Pop, H., Feidt, M., Popescu, T., 2008. Thermodynamic analysis of new eco-refrigerants ammonia and dimethylether. Termotehnica 2, 75–80.

Bao, J., Yuan, T., Zhang, L., Zhang, N., Zhang, X., 2019. Comparative study of three boil-off gas treatment schemes: From an economic perspective. Energy Convers. Manag. 201, 112185. http://dx.doi.org/10.1016/j.enconman.2019.112185.

Bluegold Research, 2020. Regional LNG Prices (Monthly Average). Bluegold Res, https://bluegoldresearch.com/regional-lng-prices. (Accessed 6 September 2020).

CEIC, 2018. China CN: Market Price: Monthly Avg: Organic Chemical Material: Dimethyl Ether: 99.0% Or above. Ceic, https://www.ceicdata.com/en/china/china-petroleum--chemical-industry-association-petrochemical-price-organic-chemical-material/cn-market-price-monthly-avg-organic-chemical-material-dimethyl-ether-990-or-above.

Chang, D., 2017. Note on critical issues with boil-off gas generating from marine fuel LNG. Oceanogr. Fish. Open Access J. 1, http://dx.doi.org/10.19080/OFOAJ.2017.01.555568.

Cho, J., Lim, G.J., Kim, S.J., Biobaku, T., 2018. Liquefied natural gas inventory routing problem under uncertain weather conditions. Int. J. Prod. Econ. 204, 18–29. http://dx.doi.org/10.1016/j.ijpe.2018.07.014.

Collodi, G., 2010. Hydrogen production via steam reforming with CO_2 capture. Chem. Eng. Trans. 19, 37–42. http://dx.doi.org/10.3303/CET1019007.

Dahl, C.A., 2006. Book Review - International Energy Markets: Understanding Pricing, Policies, and Profits, Vol. 27. PennWell Corporation, http://dx.doi.org/10.5547/issn0195-6574-ej-vol27-no1-9.

DNV GL, 2019. Maritime Assessment of Selected Alternative Fuels and Technologies, Vol. 391.

Engines, T., 2013. Propulsion trends in LNG carriers.

Eveloy, V., Gebreegziabher, T., 2018. A review of projected power-to-gas deployment scenarios. Energies 11. http://dx.doi.org/10.3390/en11071824.

Filippone, A., 2014. Green aviation. https://org.ezproxy.kustar.ac.ae/10.1036/1097-8542.YB140406.

GIIGNL, 2019. The LNG Industry GIIGNL Annual Report. Tokyo.

Gómez, J.R., Gómez, M.R., Garcia, R.F., Catoira, A.D.M., 2013. On board LNG reliquefaction technology: a comparative study. Polish Marit. Res. 21, 77–88. http://dx.doi.org/10.2478/pomr-2014-0011.

Good, D.A., Francisco, J.S., Jain, A.K., Wuebbles, D.J., 1998. Lifetimes and global warming potentials for dimethyl ether and for fluorinated ethers: CH_3OCF_3 (E143a), CHF_2OCHF_2 (E134), CHF_2OCF_3 (E125). J. Geophys. Res. Atmos. 103, 28181–28186. http://dx.doi.org/10.1029/98JD01880.

Jia, W., Lin, Y., Yang, F., Li, C., 2020. A novel lift-off diameter model for boiling bubbles in natural gas liquids transmission pipelines. Energy Rep. 6, 478–489. http://dx.doi.org/10.1016/j.egyr.2020.02.014.

Kajaste, R., Hurme, M., Oinas, P., 2018. Methanol-Managing greenhouse gas emissions in the production chain by optimizing the resource base. AIMS Energy 6, 1072–1102. http://dx.doi.org/10.3934/energy.2018.6.1074.

Kamalinejad, M., Sheykhbahaee, A., Mazaheri, S., 2016. Financial feasibility study between purchasing and hiring LNG carrier in Iranian LNG industry. p. 1.

Khan, M.I., 2018. Comparative Well-to-Tank energy use and greenhouse gas assessment of natural gas as a transportation fuel in Pakistan. Energy Sustain. Dev. 43, 38–59. http://dx.doi.org/10.1016/j.esd.2017.12.004.

Kim, N.-H., 2016. Application of the natural refrigerant mixture R-290/DME to a soft ice cream refrigerator. Int. J. Air-Condition. Refrig. 24, http://dx.doi.org/10.1142/S2010132516500279, 1650027.

Kim, D., Hwang, C., Gundersen, T., Lim, Y., 2019. Process design and economic optimization of boil-off-gas re-liquefaction systems for LNG carriers. Energy 173, 1119–1129. http://dx.doi.org/10.1016/j.energy.2019.02.098.

Kurle, Y.M., Wang, S., Xu, Q., 2017. Dynamic simulation of LNG loading, BOG generation, and BOG recovery at LNG exporting terminals. Comput. Chem. Eng. 97, 47–58. http://dx.doi.org/10.1016/j.compchemeng.2016.11.006.

Li, Y., Chen, X., Chein, M.-H., 2012. Flexible and cost-effective optimization of BOG (boil-off gas) recondensation process at LNG receiving terminals. Chem. Eng. Res. Des. 90, 1500–1505. http://dx.doi.org/10.1016/j.cherd.2012.01.013.

Liu, C., Zhang, J., Xu, Q., Gossage, J.L., 2010. Thermodynamic-analysis-based design and operation for boil-off gas flare minimization at LNG receiving terminals. Ind. Eng. Chem. Res. 49, 7412–7420. http://dx.doi.org/10.1021/ie1008426.

Magraw, K., 2017. I.32 United Nations Conference on Trade and Development (UNCTAD). Elgar Encycl. Int. Econ. Law. Edward Elgar Publishing, pp. 73–76. http://dx.doi.org/10.4337/9781784713546.45.

Methanex, 2015. Methanex Methanol Price Sheet, Vol. 1. Methanex Corp, https://www.methanex.com/sites/default/files/methanol-price/Mx-Price-Sheet-2015-11-27.pdf.

Moon, J.W., Lee, Y.P., Jin, Y.W., Hong, E.S., 2007. Cryogenic refrigeration cycle for re-liquefaction of LNG boil-off gas. Cryocoolers 14, 629–635.

Morgan, E.R., 2013. Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind (Ph.D. diss). Univ Massachusetts, Amherst, p. 432.

Natural Gas Global, 2015. Technical requirements on LNG quality. Nat. Gas Glob. Mag. http://naturalgasglobal.com/2015/07/23/technical-requirements-on-lng-quality/.

Niemi, E.G., 2017. The social cost of carbon. In: Encycl Anthr, Vol. 1–5. pp. 475–478. http://dx.doi.org/10.1016/B978-0-12-809665-9.09954-7.

Nwaoha, C., Wood, D.A., 2014. A review of the utilization and monetization of Nigeria's natural gas resources: Current realities. J. Nat. Gas Sci. Eng. 18, 412–432. http://dx.doi.org/10.1016/j.jngse.2014.03.019.

PortWorld, 2012. Portworld distance - ship voyage distance calculator. http://www.portworld.com/map/.

Pospíšil, J., Charvát, P., Arsenyeva, O., Klimeš, L., Špiláček, M., Klemeš, J.J., 2019. Energy demand of liquefaction and regasification of natural gas and the potential of LNG for operative thermal energy storage. Renew. Sustain. Energy Rev. 99, 1–15. http://dx.doi.org/10.1016/j.rser.2018.09.027.

Qatargas, 2018. Qatargas' Chartered Fleet. Qatargas Oper Co Ltd, http://www.qatargas.com/english/operations/qatargas-chartered-fleet.

QatarGas, 2020. North Field. Qatargas Oper Co Ltd, http://www.qatargas.com/english/aboutus/north-field.

Romero Gómez, J., Romero Gómez, M., Lopez Bernal, J., Baaliña Insua, A., 2015. Analysis and efficiency enhancement of a boil-off gas reliquefaction system with cascade cycle on board LNG carriers. Energy Convers. Manag. 94, 261–274. http://dx.doi.org/10.1016/j.enconman.2015.01.074.

Schnitkey, G., 2018. Nitrogen prices, rates cuts, and 2018 fertilizer costs. In: Farmdoc Dly, Vol. 58, No. 8. Dep Agric Consum Econ Univ Illinois Urbana-Champaign, https://farmdocdaily.illinois.edu/2018/04/nitrogen-prices-rates-cuts-and-2018-fertilizer-cost.html, Apr 3.

Seddon, Duncan, 2006a. Gas Transport. Gas usage and value: The technology and economics of natural gas use in the process industries. PennWell Corp, Tulsa, pp. 85–103.

Seddon, Duncan, 2006b. Chemical Intermediates. Gas Usage and Value: The Technology and Economics of Natural Gas Use in the Process Industries. PennWell Corporation, Tulsa, pp. 133–260, 1-59370-073-3.

Semelsberger, T.A., Borup, R.L., Greene, H.L., 2006. Dimethyl ether (DME) as an alternative fuel. J. Power Sources 156, 497–511. http://dx.doi.org/10.1016/j.jpowsour.2005.05.082.

Shah, Y.T., 2017. Chemical energy from natural and synthetic gas. http://dx.doi.org/10.1201/9781315302355.

Sharples, J., 2019. LNG supply chains and the development of LNG as a shipping fuel in Northern Europe. http://dx.doi.org/10.26889/9781784671266.

Singapore Bunker Prices, 2020. Ship & bunker. Sh bunker. https://shipandbunker.com/prices/apac/sea/sg-sin-singapore#IFO180.

Social Cost of Carbon, 2016. High educ whisperer. http://scholar.aci.info/view/1488df20b53381d035a/15355485d8a00150002. (Accessed 6 May 2020).

Software F-Chart, 2015. EES: Engineering equation solver: Engineering software.

Tan, H., Shan, S., Nie, Y., Zhao, Q., 2018. A new boil-off gas re-liquefaction system for LNG carriers based on dual mixed refrigerant cycle. Cryogenics 92, 84–92. http://dx.doi.org/10.1016/j.cryogenics.2018.04.009, (Guildf).

Tan, H., Zhao, Q., Sun, N., Li, Y., 2016. Enhancement of energy performance in a boil-off gas re-liquefaction system of LNG carriers using ejectors. Energy Convers. Manag. 126, 875–888. http://dx.doi.org/10.1016/j.enconman.2016.08.031.

Xu, Wang, Shah, Zameer, Solangi, Walasai, et al., 2019. Economic viability and environmental efficiency analysis of hydrogen production processes for the decarbonization of energy systems. Processes 7, 494. http://dx.doi.org/10.3390/pr7080494.