Process design and economic optimization of boil-off-gas re-liquefaction systems for LNG carriers

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Abstract

Recent LNG carriers are equipped with high pressure gas injection engines. However, there has been a lack of research on liquefaction processes for boil-off gas (BOG) on LNG ships driven by high pressure fuel. Thus, this paper investigates the economic feasibility of the additional BOG liquefaction facilities in the high pressure fuel supply system on the vessels. To utilize the existing BOG compressor for fuel production, the liquefaction was conducted by the Joule Thomson (JT) cycle, which can use the pressurized BOG as a working fluid. For the comparison of the fuel supply system and its variations with BOG liquefaction, they are optimized with respect to total annual cost (TAC) as the objective function. With an LNG price of 5 USD/MMBtu, the optimization results show that the use of BOG liquefiers on LNG vessels reduces the TAC by at least 9.4 % compared to the high pressure fuel supply system. The use of a liquid turbine in the liquefaction configurations also resulted in 2.4 % savings in TAC compared to the JT cycle based process. However, a sensitivity analysis with different LNG prices indicates that the liquefaction systems are not economical compared to the fuel supply system when the LNG price is lower than 4 USD/MMBtu.

1. Introduction

Following the event when liquefied natural gas (LNG) was produced by external refrigerants and Joule-Thomson throttling for commercial purposes in 1941, the first long-haul transport of LNG was made from Louisiana in the US to Canvey Island in the UK in 1959 [1, 2]. This successful shipment resulted in LNG becoming an attractive option to supply energy over long distances, where it is not economical to use pipeline transmission of natural gas [3, 4]. Thus, LNG has been an important solution for energy security in many countries such as Japan and Korea, accounting for 10 % of global gas supply [5].

For the transportation of LNG, specially designed vessels with highly insulated storage tanks are used to avoid evaporation of the valuable cargo during a voyage [2, 6]. Nevertheless, it is inevitable to have heat leaks to the tanks, and a portion of LNG will vaporize on the liquid surface of the cargo, producing boil-off gas (BOG) [7]. The sloshing of LNG in the storage tanks due to ship motions also accelerates BOG generation [8]. Since the BOG increases the pressure level of the storage tanks and thus the mechanical stress of the structure, it has to be removed from the containment system [9].

In order to remove or utilize the BOG from the tank, steam turbine (ST) propulsion systems have been widely used since the 1960s [10-12]. The unnecessary BOG is burned in boilers to produce steam, which is fed to STs and turbo generators to supply propulsion and electric power [12, 13]. However, the ST system has a lower thermal efficiency compared to heavy fuel oil (HFO) driven two-stroke low speed diesel engines, which is the main propulsion principle for commercial ships [10-12, 14, 15]. This low efficiency of STs may require extra fuel supplied by the LNG cargo for modern LNG carriers, which minimize BOG production due to improved insulation technology. The larger amount of carbon dioxide in the exhaust gas compared to the internal combustion engines also made the ST propulsion system less favorable for LNG vessels.

In addition to low efficiency, STs have two additional disadvantages: First, improved insulation technologies [12] reduce the amount of BOG available. Second, the larger amount of carbon dioxide in the exhaust gas from the boiler will causes problems for LNG vessels, where the International Maritime Organization (IMO) recently extended their restriction about CO_2 emission [11].

Thus, a dual fuel diesel electric (DFDE) propulsion system was developed in the early 2000s to use both HFO and BOG as fuel for diesel engines, which delivers a higher efficiency with less pollution compared to STs [10, 12, 14]. The DFDE system supplies a mixture of the pre-treated BOG and air into four-stroke diesel generator engines in order to produce electric power for motor-driven propellers and other electricity needs on the LNG vessel [13]. This system is also equipped with gas combustion units (GCU) to burn the surplus of BOG after being consumed as fuel. The DFDE quickly dominated the market share, and 30 % of the current LNG fleet is operated by this propulsion system [5].

However, the DFDE propulsion system does not fully utilize the power output of diesel engines due to the extra units required to deliver the combustion energy from the engines to the propellers such as electrical generators and propulsion motors [10, 12]. This electric system also requires additional parts, which demand more maintenance efforts [14]. As a consequence, ship engine manufacturers modified the conventional HFO fueled two-stroke slow speed diesel engines to adapt BOG as fuel and directly drive the impellers, which is more efficient than the four-stroke machinery applied to the DFDE [11, 16]. The injection of compressed BOG fuel into the engine cylinders enables the newly developed diesel engines to achieve the same efficiency as the conventional HFO driven diesel engines [16].

There are two main manufacturers providing such engines on the market: Man Diesel & Turbo with the M-type electronically controlled gas injection (ME-GI) engine and Win GD with the extra-long stroke dual fuel (X-DF) engine [17, 18]. The ME-GI system feeds high pressure BOG to the cylinders after the compression stroke, which is close to the Diesel cycle [16]. In contrast, the X-DF engine allows supplying relatively low pressure BOG to the combustion chamber by injecting it in the middle of the compression stroke, thus working as an Otto cycle [18]. As of 2018, there were 18 LNG vessels operated by the ME-GI based system and around 42 % of LNG carriers in the order books will be built with the high pressure gas injection engine [5].

With the improved efficiency of the propulsion system, less BOG is consumed as fuel on voyages, and the rest is burned in a GCU. The amount of BOG treated in the GCU is a significant economic loss of the cargo, and this increases during low load operations. Thus, there have been various suggestions for the ME-GI based propulsion system to re-liquefy the valuable product and return it to the LNG tanks. The EcoRel system from Cryostar liquefies BOG through a nitrogen gas expander refrigeration cycle [17, 19]. A part of the liquefied BOG is then sent to the storage tank, and the rest is pressurized by LNG pumps and vaporized to be fed to the engine. Wärtsilä (Hamworthy) also supplies a re-liquefaction system (the Mark III type), having similar principles as the EcoRel [17, 20]. The drawback of these two processes is that the entire BOG is always liquefied although some part of the liquid product has to be re-vaporized as fuel for the engines, wasting the cold energy.

Instead, Wärtsilä (Hamworthy) modified the Mark III system so that BOG is pressurized in gas phase by the Laby-GI compressors (reciprocating type) to supply fuel for the propulsion system [17]. Thus, the BOG from the cargo tank does not need to be liquefied all the time, and this can save energy consumed in the liquefaction cycle when liquefaction of BOG is not required during voyages. However, some of the energy savings will be offset by the larger power consumption in the compressor, compared to liquid compression in the pumps. TGE Marine Gas Engineering also offers a cascade liquefaction system with the Laby-GI compressors in order to overcome the inherent low efficiency of the N_2 expander refrigeration cycle [21].

Although the above mentioned liquefaction technologies minimize the amount of LNG wasted in the form of BOG and bring a larger amount of the cargo to LNG import terminals, they need extra equipment and increased capital cost. One of the alternatives is to employ a less efficient but simpler liquefaction system such as the Joule-Thomson (JT) cycle. This process, also known as the Linde-Hampson process, compresses a feed gas above the critical pressure and depressurizes it through a JT valve in order to liquefy the gas by temperature drop without an external refrigerant [22]. The use of the self-reliquefaction process in the propulsion system with the high pressure gas injection engine will only require a heat exchanger and a phase separator in addition to the Laby-GI compressor where the pressurization of BOG is achieved. The simple structure of the JT cycle will reduce the number of units and thus capital cost for a BOG liquefaction facility, while accepting a reasonable increase in power consumption due to the low efficiency of the process. However, previous literature mainly focuses on BOG reliquefaction processes (including the JT cycle) for the DFDE propulsion system [8, 23-27].

Therefore, this paper suggests self-reliquefaction processes using the JT cycle for the propulsion system with high pressure gas injection engines on LNG carriers. The costs of the reliquefaction system are estimated and compared with the propulsion scheme without BOG reliquefaction in order to ensure the economic feasibility of the additional JT cycle based processes. The capital and operating costs of the systems are calculated based on equipment size, wasted BOG, and utility consumption. For a fair comparison, all the propulsion systems are optimized using a stochastic algorithm to minimize the capital and operating cost by finding proper operating conditions for the total system. Various improved process schemes are also suggested to reduce the total cost while keeping the number of equipment low. A sensitivity analysis is also performed with respect to LNG price, since this is one of the most important parameters affecting the economics of the liquefaction system.

2. Propulsion system with high pressure gas injection engines

2.1 Fuel supply system without BOG liquefaction

The propulsion system considered in this paper has two types of engines; generating electricity (DFDE engines) and driving the propeller of the vessel (high pressure gas injection engines). Thus, as seen in Figure 1, the fuel supply system requires two fuel gas streams with different pressure specifications. First, the BOG produced in the storage tank is sent to the first compressor (K-1). Due to the cryogenic temperature of stream B1 at the inlet of K-1, the outlet stream of the compressor (B2) has a low enough temperature to avoid any intercooling for further compression. Then, the unnecessary part of stream B2 is fed to the GCU to be burned.

The rest of the BOG is further pressurized through the second compressor (K-2) and cooled by the intercooler (IC-1). The intermediate pressure BOG (B6) is then split into streams B7 and B8, which will be supplied to the DFDE generators and the high pressure compressors, respectively. Stream B8 is passed through a three-stage compression (K-3 – K-5) and intercooling (IC-2 – IC-4) to meet the fuel requirement and then delivered to the propulsion engines. If there is a lack of BOG to run the two engines, LNG from the storage tank is extracted to supply additional fuel for the gas injection engines. This LNG is boosted by the high pressure pump (LNG pump) and evaporated in a heat exchanger (LNG vaporizer). In this paper, the LNG supply scheme is not considered, assuming that BOG produced in the tanks is sufficient to operate the propulsion system. The system described in Figure 1 is referred to as the reference fuel supply system in this paper.

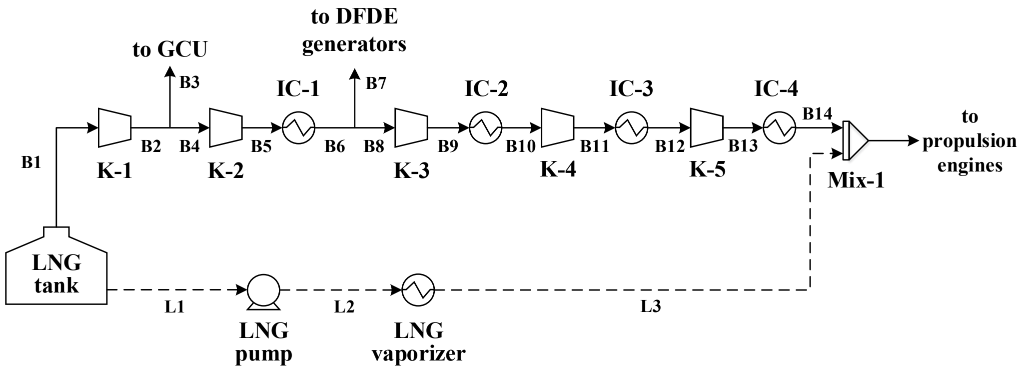

Figure 1. Process flow diagram for the fuel supply system without BOG liquefaction.

2.2 Fuel supply system with BOG liquefaction

The reference fuel supply system is modified to include the BOG self-reliquefaction system. The re-liquefaction is performed by extracting a relatively high pressure BOG during multi-stage compression in order to use it as a refrigerant in the JT cycle for BOG liquefaction. Thus, a part of the pressurized BOG (B16) from the fourth compressor (K-4) is recycled to the cryogenic heat exchanger (CHE) after being cooled by the intercooler (IC-4) as seen in Figure 2. Due to friction in the long return pipeline, the pressure level of the recycled stream (R1) is reduced and supplied to the cold box where it is liquefied. The pre-cooled and liquefied BOG stream from the CHE (R2) is then depressurized through JT valve VLV-1. The throttled stream R4 is separated to liquid (R5) and vapor (R7) products in the phase separator. Stream R5 is returned to the LNG storage tank after adjusting the pressure level by another JT valve (VLV-2) to be suitable for injection into the tank. Stream R7 is further depressurized by JT valve VLV-3 to have the same pressure level as the BOG from the tank (B1). The two gas streams are mixed and sent to heat exchanger CHE to supply cold duty. This process is referred to as the JT process.

Unlike the reference system, the inlet stream of the compressor K-1 does not have a cryogenic temperature since the mixed stream (B2) is heated in heat exchanger CHE. Thus the fuel supply system with BOG liquefaction will require an extra intercooler (IC-1) to cool the superheated outlet stream of the first compressor. If, however, the outlet temperature of compressor K-1 is equal to or lower than that of the intercoolers, the intercooler IC-1 will be disregarded during simulation and economic evaluation of the system.

One of the possible modifications of the system is the use of a cryogenic liquid turbine (LT) together with the JT valve (VLV-1) for the depressurization process of the high pressure liquefied BOG (R2). Since LTs can be used in a limited range of pressure drop to avoid vapor production at the outlet, a JT valve is also installed downstream to take the rest of the pressure change required in the system. The LT in the liquefaction process allows stream R2 to have an isentropic expansion, resulting in a larger temperature reduction and smaller vapor fraction in the outlet stream with a given pressure drop compared to isenthalpic expansion in JT valves [28]. Thus, through the phase separator, the combination of an LT and a JT valve will produce a larger amount of liquid product (LNG) and a colder vapor stream, which is used as part of the refrigerant in the system. Besides, the LT converts the pressure energy into work, decreasing the total power consumption of the fuel supply system although the turbo-machinery requires extra capital cost. Thus, in this paper, the use of the LT in the fuel supply system with BOG liquefaction is considered as an option to improve the economics of the total system and compared with the case without the LT. This process configuration is referred to as the LT-JT system.

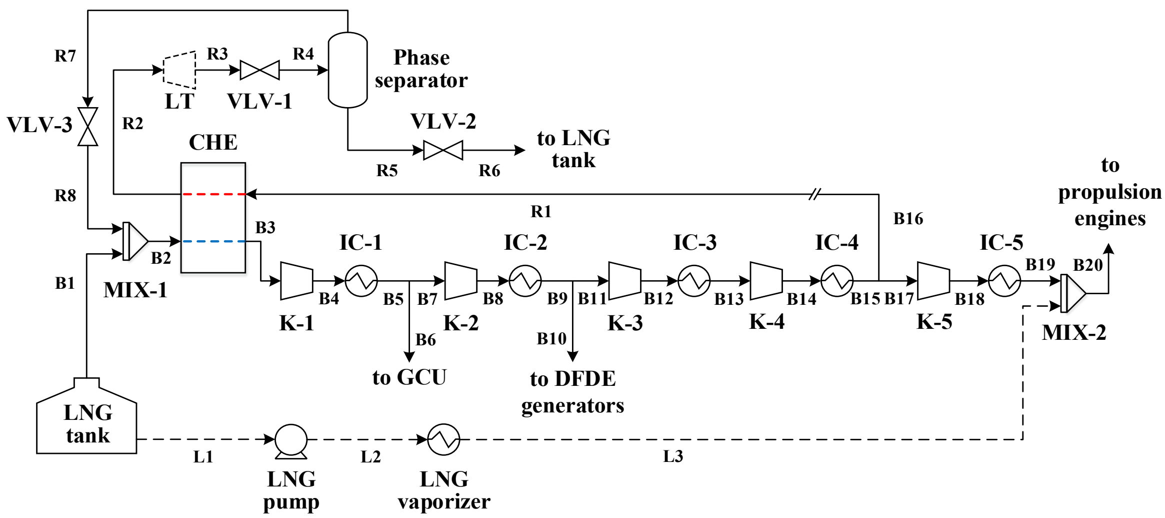

Figure 2. Process flow diagram for the fuel supply system with the LT process (the LT-JT process is indicated by the dotted equipment LT).

2.3 Utilization of the recycled cold BOG

The top product from the phase separator tends to have a much lower temperature than the BOG from the LNG tanks. However, the previous schemes do not utilize the cold energy of stream R8, instead it is mixed with the BOG (B1), thus increasing entropy generation due to the temperature difference. Instead, as seen in Figure 3, the two cold streams can be sent to heat exchanger CHE separately to deliver their cold energy and then mixed at the outlet of the exchanger. Although the low temperature of stream R8 increases log mean temperature difference (LMTD) of the CHE and thus entropy generation, such large temperature difference results in smaller heat exchanger area, reducing the cost of the exchanger. In addition, the two cold streams at the CHE outlet have almost the same temperature, resulting in smaller entropy generation through the mixer (MIX-1). Stream R8 will also make it possible to manipulate design parameters of the CHE, such as LMTD and heat exchanger area by controlling the two JT valves (VLV-1 and VLV-3), and thus the temperature and pressure of stream (R8). This modification is referred to as the LP mix LT-JT process.

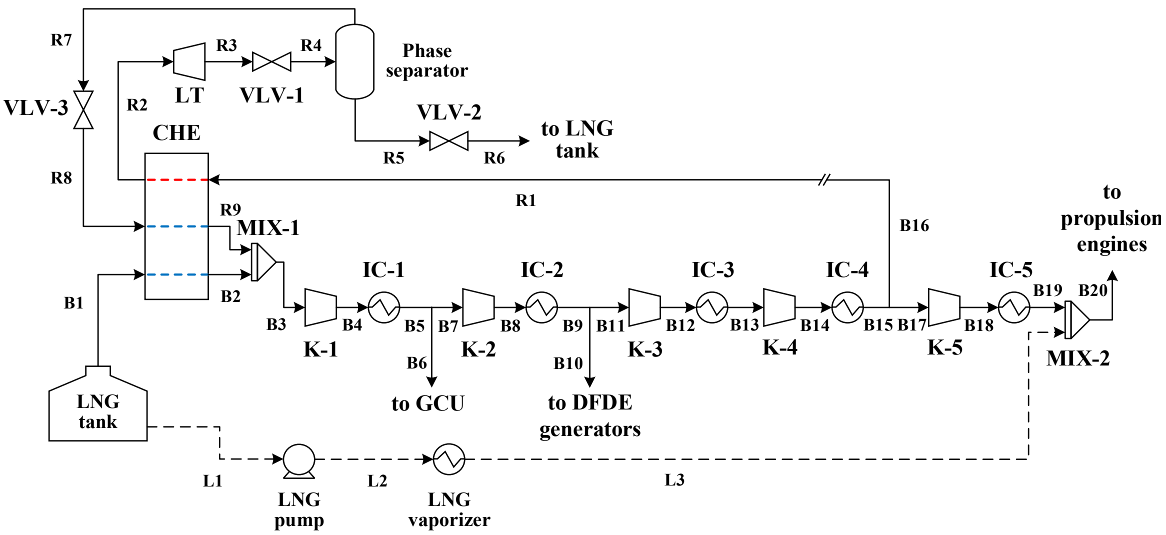

Figure 3. Process flow diagram for the fuel supply system with the LP mix LT-JT process.

Due to the mixing process in the LP mix LT-JT system, the vapor product from the phase separator (R7) has to be throttled by JT valve VLV-3 to the pressure level of stream B1, which is just above atmospheric pressure. As an alternative, the CHE outlet stream of the recycled BOG (R9) can be mixed with the slightly pressurized BOG stream (B6) (see Figure 4). This configuration is referred to as the IP mix LT-JT process. Since stream R9 bypasses compressor

K-1 and intercooler IC-1, the duties of the turbo-machinery and the heat exchanger are reduced, saving both capital and operating costs.

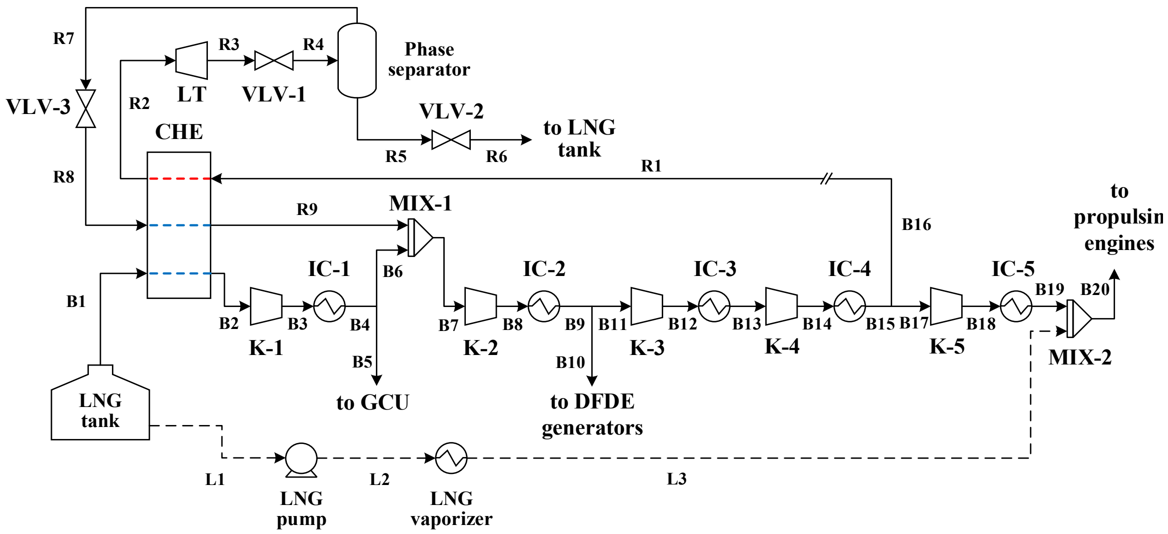

Figure 4. Process flow diagram for the fuel supply system with the IP mix LT-JT process.

Using the same principle as the IP mix LT-JT system, the recycled BOG stream (R9) heated in the CHE can be mixed with the high pressure BOG stream (B10), thus bypassing two stages of compression and intercooling. Figure 5 shows the configuration with the high pressure mixing, which is referred to as as the HP mix LT-JT process. If stream R9 is mixed with the BOG streams from the third or fourth compressors (K-3 and 4), the throttling pressure at VLV-1 will be limited to the discharge pressure of the compressors, which is more than 40 bar. Due to the high throttling pressure, vapor will not form in the JT valve and the structure of the process will be identical to the LT-JT process, except there is no flow in the phase separator top product (stream R7 and R8). Therefore, further mixing of the recycled BOG with other compressor outlet streams is not considered in this paper.

The three configurations utilizing the recycled BOG are also tested without the liquid turbine in consideration of the downtime for the turbo-machinery. They are referred to as the LP, IP and HP mix JT processes. This test will indicate the effect of the modified process schemes on the liquefaction systems using only Joule Thomson valves.

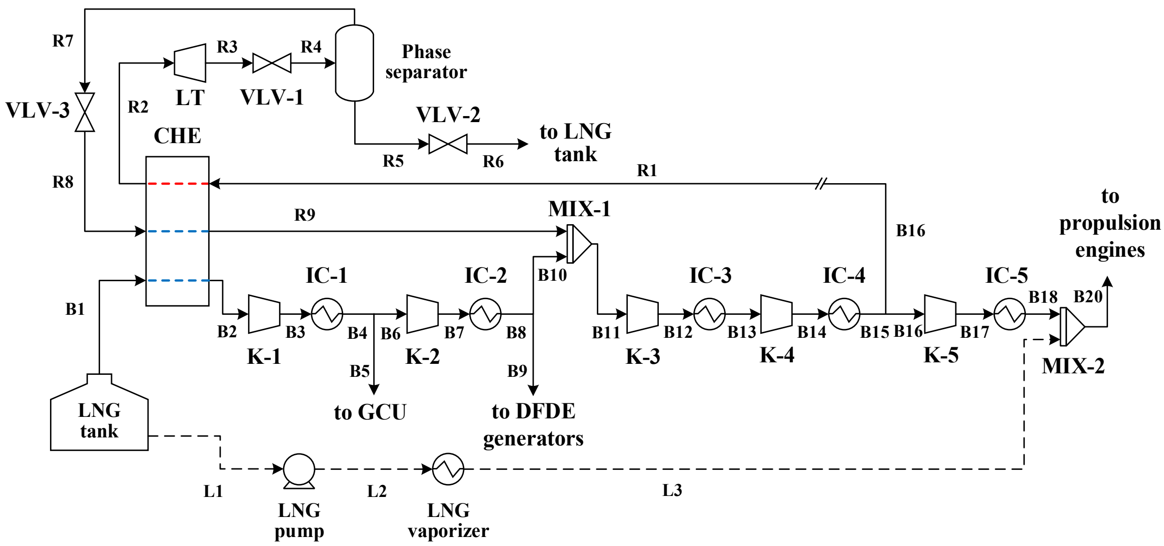

Figure 5. Process flow diagram for the fuel supply system with the HP mix LT-JT process.

3. Design basis

3.1 Simulation conditions

In this work, the scope of simulation models was limited to the fuel supply systems and the liquefaction processes on LNG carriers. Thus, other sub-systems related to LNG tanks, gas combustion units, propulsion engines, and cooling water systems were not considered. In addition, the auxiliary fuel supply system using LNG is also beyond the scope as mentioned Section 2.1. The fuel supply systems were modeled and simulated by using Aspen HYSYS V9 with the Peng-Robinson equation of state (EOS) [29]. Heat leaks are neglected for all the process units in the systems, assuming that these are highly insulated. However, it should be noticed that the imperfect insulation in real cases will allow some heat losses, despite the fact that a high level of insulation is applied to cryogenic systems on-site. This will result in minor deviations for the simulation results. Other specifications for the equipment are listed in Table 1.

Table 1. Design parameters for the fuel supply system.

Parameters	Unit	Value
Compressor isentropic efficiency	%	75
Liquid expander isentropic efficiency	%	75
Intercooler outlet temperature	°C	45
Intercooler Δp	bar	0.5
Heat exchanger ΔT_{min}	°C	3
Heat exchanger Δp	bar	0.03 - 1

3.2 BOG feed

The LNG stored in the cargo tanks is assumed to have a composition that gives a gross heating value within the acceptable range for the EU market [30]. This composition and other LNG conditions are shown in Table 2. The BOG supplied to the fuel supply system is expected to have higher temperature and lower pressure values than the stored LNG due to heat leaks and pressure drop through the cargo tanks and pipelines connected to the fuel supply system [8, 31] (see Table 3).

Regarding the amount of BOG, the calculation of the boil-off rate (BOR) of the LNG in the cargo tanks will require comprehensive CFD models since it is a complex function of the ambient temperatures (air and sea water), characteristics of the tanks (dimensions and thickness), and vessel movement [9]. Besides, the vaporization of the lighter components in the LNG will continue during voyages, making the LNG rich in heavier hydrocarbon components. The composition change in the stored LNG with time is known as the weathering (aging) process, and this also affects the vaporization mechanism and thus the amount and the composition of the BOG in the tank [7]. In industry, 0.1 to 0.15 vol % of stored LNG per day is known as a typical BOR for LNG vessels [6-8]. Thus, a constant value of BOR is applied in this work to estimate the amount of BOG as seen in Table 2. With the given BOR, the amount of BOG can be calculated by

$$\dot{m}_{\mathrm{BOG}} = r_{\mathrm{BOR}} \cdot V_{\mathrm{tank}} \cdot Lv_{\mathrm{tank}} \cdot \rho_{\mathrm{LNG}} \tag{1}$$

where r_{BOR} is the rate of boil-off, V_{Tank} is the total volume of the storage tanks, Lv_{Tank} is the average liquid level of the tanks in percentage, and ρ_{LNG} is the density of the LNG [32]. In this work, a typical large size LNG carrier with membrane type storage tanks (a volume of 170,000 m^3) is considered, and 95 vol % of the tanks are assumed to be filled with cargo. Thus, based on Eq. (1), 2946.5 kg/h of BOG is thought to be generated during voyages. In the simulation model, a uniform heat input to the storage tanks was assumed to produce the given amount of BOG, and the corresponding composition is shown in Table 3.

Table 2. The conditions of the stored LNG.

Parameters	Unit	Value
LNG composition		
Nitrogen	mol %	0.37
Methane	mol %	95.89
Ethane	mol %	2.96
Propane	mol %	0.72
n-Butane	mol %	0.06
LNG temperature	°C	-161.80
LNG pressure	bar	1.06
LNG density	kg/m^3	437.89
BOR	vol % / day	0.1

Table 3. The conditions of BOG from the storage tank.

Parameters	Unit	Value
BOG composition		
Nitrogen	mol %	0.48
Methane	mol %	99.49
Ethane	mol %	0.03
BOG temperature	°C	-120.00
BOG pressure	bar	1.06
JT coefficient of BOG[a]	°C /bar	1.14

[a]BOG at -120 °C and 1.06 bar.

3.3 Products

Two DFDE generators are assumed to be operated at 50 % load to produce 4000 kW to supply the electricity needed on the LNG vessel. The specific fuel oil consumption (SFOC) with gas fuel operation is 7671 kJ/kWh for the generators from the reference model by assuming an intermediate engine load with power production [33]. For the engines, the MAN Diesel & Turbo 5G70 model is considered to deliver the power output of 9938 kW for an intermediate speed voyage, and the SFOC is assumed to be 6280 kJ/kWh [17]. The required mass flow rates of fuel to the engines for electricity production and propulsion power are then obtained from Eq. (2).

$$\dot{m}_{\text{fuel}} = \frac{P_{\text{engine}} \cdot SFOC_{\text{engine}}}{LHV_{\text{fuel}}} \tag{2}$$

where P_{engine} and $SFOC_{\text{engine}}$ are the power requirement and the SFOC of the engines, and LHV_{fuel} is the lower heating value (LHV) of the two fuels. Except for the reference fuel supply system, the mass flow rates of the two fuels will vary since the LHV depends on the composition, which is changing due to the recycled BOG and its liquefaction ratio.

The re-liquefied BOG is throttled to 2.5 bar, and the two-phase stream is sent to the LNG cargo tanks. Thus, the vapor product is mixed with the BOG produced in the storage tanks and recycled to the fuel supply system. The pressure level of the BOG extracted for the GCU is specified to 3.5 bar in order to overcome pressure drops in pipelines and auxiliary equipment [17, 34]. Table 4 indicates other conditions for the fuels and re-liquefied BOG applied in this paper.

Table 4. Specifications of the products.

Parameters	Unit	Value
DFDE fuel temperature	°C	45
DFDE fuel pressure	bar	11.5
DFDE fuel mass flow rate[a]	kg/h	621
Propulsion fuel temperature	°C	45
Propulsion fuel pressure	bar	300
Propulsion fuel mass flow rate[a]	kg/h	1262
Re-liquefied BOG pressure	bar	2.5
BOG pressure for GCU	bar	3.5

[a]Only for the reference fuel supply system.

4. Economic analysis and optimization

4.1 LNG price and BOG loss

Initially, the LNG price is set to 5 USD/MMBtu (1MMBtu = 1055 MJ) by assuming that the LNG carrier sails from the US to Spain [35]. This price is used to estimate the economic loss of the BOG burned in the GCU. The amount of BOG wasted will differ based on the voyage status of the LNG carrier. During voyages, the BOG will be used for the engines, and the rest is sent to the GCU. During the unloading of the cargo at an import terminal, it is assumed that only the DFDE is operated and the surplus of the BOG is burned. Thus, for the estimation of the amount of BOG burned in a year, the voyage schedule is considered as seen in Table 5. In this paper, an annual vessel operation with 12 cycles is considered.

Table 5. The voyage schedule of the LNG vessel.

Parameters	Unit	Value
Voyage speed	kts	15.5
Voyage	d/cycle	12
Unloading	d/cycle	0.5
Number of cycles	cycles/yr	12

4.2 Cost evaluation

The total annual cost (TAC) is estimated [36] for the reference fuel supply system and the other configurations with BOG liquefaction in order to evaluate the economic advantage of the additional liquefaction facilities. The TAC consists of the annual total capital investment (ATCI), the annual total operating cost (ATOC), and the cost related to the annual BOG losses as seen in Eq. (3).

$$TAC = ATCI + ATOC + C_{\mathrm{BOG\ loss}} \tag{3}$$

Regarding the ATCI, an LNG vessel is assumed to operate for 20 years [37], and an annual interest rate of 10 % is applied to estimate the annual investment cost for the equipment.

$$ATCI = TCI \cdot \left(\frac{i(1+i)^n}{(1+i)^n - 1}\right) \tag{4}$$

where i is the annual interest rate and n is the service life of the vessel. The total capital investment (TCI) is defined by Eq. (5) where Q is the set of units in the system.

$$TCI = F_{\text{Ext}} \cdot \sum_j C_{\text{P}}^j \cdot F_{BM}^j, \qquad j \in \text{Q} \tag{5}$$

C_{P}^j represents the purchased cost of equipment j, and F_{BM}^j is the factor for bare module costs related to operating pressure, material and installation of equipment j. The factor for bare module cost is listed in Table 6. Extra cost is also considered in estimation of TCIs by applying a factor (F_{Ext}), which is assumed to be 1.18 [36].

The purchased cost is a function of the capacity of units (A) as shown in Eq. (6) [36]. The capacity of units (A) and the coefficients (K_1, K_2, K_3) for the cost function are shown in Table 6 for various process equipment.

$$\log_{10} C_{\text{P}}^j = K_1 + K_2 \log_{10} A + K_3 (\log_{10} A)^2 \tag{6}$$

As indicated in Eq. (7), the fixed cost, the maintenance cost and the cost for supplies are estimated as a fraction of the ATCI (f_{CTO}), while the utility cost is calculated from the electricity price (v_{e}) for total power consumption in compressors and the cooling water price (v_{CW}) for the cooler duties. In this work, f_{CTO} is assumed to be 0.066 [36].

$$ATOC = F_{\text{CTO}} \cdot ATCI + \left(v_{\text{e}} \sum P_{comp} + v_{\text{CW}} \sum D_{\text{CW}} \right) \tag{7}$$

The annual cost for BOG loss is represented by Eq. (8) where the sum of the annual BOG loss during voyages and unloading is considered based on the voyage schedule.

$$C_{\text{BOG loss}} = v_{LNG} \cdot N_{\text{cycle}} \cdot \left(E_{\text{BOG loss}}^{\text{voyage}} \cdot t_{\text{voyage}} + E_{\text{BOG loss}}^{\text{unloading}} \cdot t_{\text{unloading}} \right) \tag{8}$$

Table 6. Capacity of units and coefficients for capital cost calculation [36].

Equipment	A	F_{BM}	K_1	K_2	K_3
Compressor	Power [kW]	7	2.29	1.36	-0.10
Liquid Turbine	Power [kW]	6.2	2.25	1.50	-0.16
Heat exchanger	Area [m^2]	4.3	4.67	-0.16	0.15
Intercooler	Area [m^2]	3.3-8.8	2.77	0.73	0.08
Phase separator	Volume [m^3]	10.3-36.9	3.50	0.45	0.11

4.3 Optimization

The reference fuel supply system and its modifications with BOG liquefaction were optimized applying the same optimization formulation for a fair comparison. The optimization studies were performed to minimize the TAC with the decision variables **x** as seen in Eq. (9).

$$\begin{aligned} &\min_{\mathbf{x}} f(\mathbf{x}) = TAC \\ &\text{subject to} \quad \Delta T_{\text{min,CHE}} \geq 3 \\ &\qquad \Delta p_{\text{VLV}-1} \geq 0 \\ &\qquad x_{\text{LT,out}}^{\text{vap}} = 0 \\ &\qquad 1.5 \leq Pr_{\text{K}-5} \leq 4 \\ &\qquad \mathbf{x}_{LB} \leq \mathbf{x} \leq \mathbf{x}_{UB} \end{aligned} \tag{9}$$

The outlet pressure of the first compressor was fixed to meet the pressure requirement for the BOG stream sent to the GCU. The discharge pressures of the second and fifth compressors were specified to meet the fuel pressure requirements for the DFDE and the propulsion engines. The system was optimized by varying the pressure ratio of only the third and fourth compressors from 1.5 to 4, considering practical issues [38]. To avoid a high pressure ratio of compressor K-5 due to low discharge pressure of the fourth compressor (K-4), the ratio was constrained to be below 4.

The precooling temperature of the recycled BOG and the outlet pressure of valve VLV-1 were also manipulated as decision variables. Besides, the mass flow rate of the BOG sent to the GCU was selected as a key variable, which will affect the capacity of the liquefaction facility and its cost. The upper bound of the variable was set to the BOG flow rate supplied to the GCU in the reference system. If the system contains an LT, the outlet pressure of the turbo-machinery was also included as a variable in the optimization formulation. The vapor fraction of the outlet stream from the LT was constrained to 0 to avoid efficiency drop due to vapor production in the turbo-machinery [39, 40]. Since there is an overlap in the ranges for the variables of the outlet pressures between the LT and the JT device (VLV-1), the pressure drop through the valve was restricted to be larger than zero.

The pressure levels and precooling temperature of the recycled BOG are the main variables affecting the performance of the JT cycle used in the BOG liquefaction systems. In the JT cycle, the cooling effect is achieved when a JT valve has a positive JT coefficient (temperature change through the valve per unit pressure drop) during the throttling of the real gas [22]. Since the JT coefficient is dependent on the inlet temperature of the JT valve and the pressure levels of the valve inlet and outlet, they are optimized to maximize the coefficient. A larger JT coefficient will give an increased cooling effect with less pressure drop, which will reduce the boosting pressure of the BOG and thus the compression work.

A minimum temperature difference of 3 K in the cryogenic heat exchanger was also applied to constrain the processes, which is the value that reflects a balanced trade-off between capital and operating cost of the system [41, 42].

The optimization was performed by the particle swarm optimization (PSO) algorithm. PSO is a derivative-free stochastic algorithm based on candidate solutions (particles), thus it is suitable for black box functions where derivative information is either not available or noisy and costly if finite differences are considered [43, 44]. The optimization results for the fuel supply systems are shown in Table 7.

Table 7. Bounds for the decision variables and the best solutions obtained.

Variable	Unit	LB	UB	Optimal value					
				Reference	JT	LT-JT	LP mix LT-JT	IP mix LT-JT	HP mix LT-JT
$\dot{m}_{\mathrm{GCU}}$	kg/h	0.0	1070.4	1070.4	0.0	0.0	0.0	0.0	0.0
$Pr_{\mathrm{K-3}}$	-	1.5	4.0	3.8	3.9	3.8	3.9	3.9	3.9
$Pr_{\mathrm{K-4}}$	-	1.5	4.0	3.1	3.1	3.1	3.2	3.1	3.3
p_{R3}	bar	5.0	60.0	-	-	7.9	7.7	8.7	12.0
p_{R4}	bar	2.5[a]	20.0	-	2.5	2.5	2.5	4.0	12.0
T_{R2}	°C	-122.0	-60.0	-	-119.6	-120	-120.2	-117.4	-117.2

[a]4.0 for the LP mix LT-JT process and 12.0 for the HP mix LT-JT process.

5. Results and discussion

5.1 Comparison of process options

In this section, the simulation and optimization results for the liquefaction processes using the JT cycle and its variations are addressed and compared with the reference system. Table 8 indicates that the fuel supply systems with BOG liquefaction have a smaller total annual cost than the reference process. Although the TCI is increased by at least 2.34 million USD when the BOG liquefaction is included in the fuel supply system, the TAC is reduced by at least 9.4 % compared to the reference scheme. Therefore, with an LNG price of 5 USD/MMBtu, an additional BOG self re-liquefaction facility in the fuel supply system will provide a larger profit than the reference system. The reduced TAC will only require less than 5.6 years of extra payback time for the liquefaction facility, compared to the reference system.

Due to the additional equipment and the increase in compression power, the ATCI and the ATOC of the fuel supply systems with BOG liquefaction are more than the double compared to the reference configuration. The main contributor to the cost increment is the extra compression power and the additional heat exchanger for the liquefaction of BOG. However, the liquefaction systems managed to recover almost all the BOG wasted in the GCU in the reference process during voyages as seen in Table 8. Thus, the BOG losses in the fuel supply systems with BOG liquefaction only occur during unloading when all the BOG except for the fuel demand of the DFDE engine is burned in the GCU. Therefore, the loss of the cargo in the form of BOG through the GCU is decreased by 91.7 % compared to the reference system, thus compensating for the increased values of the ATCI and the ATOC in the liquefaction systems.

This decrease in BOG burned in the GCU during voyages also means that fuel supply systems with BOG reliquefaction will have a noticeable reduction in the total exhaust gas from the facilities, compared to the reference system. Thus, the installation of BOG reliquefaction systems on LNG carriers will be beneficial to meet the environmental regulations, which is expected to be tighter [11].

It is important to mention that the liquefaction ratios of the BOG condensation systems are less than one as seen in Table 8. This relatively low liquefaction ratio means that the BOG sent to the liquefiers do not need to be fully liquefied in order to prevent the BOG from being burned in the GCU. The result is liquefaction systems with smaller duty and TAC.

Table 8. Optimization results with process performance parameters (LNG price = 5 USD/MMBtu).

		Unit	Reference	JT	LT-JT	LP mix LT-JT	IP mix LT-JT	HP mix LT-JT
Liquefaction ratio[a]		-	-	0.75	0.80	0.80	0.83	0.97
$\dot{m}_{\mathrm{LNG}}$		kg/h	-	1063.34	1063.67	1063.70	1063.31	1062.92
$\dot{m}_{\mathrm{GCU}}$		kg/h	1070.42	0.00	0.00	0.00	0.00	0.00
P_{comp}		kW	511.09	1097.41	1071.33	1069.25	1055.61	1098.98
P_{LT}		kW	-	0.00	8.59	8.57	8.61	9.10
Specific power[b]		kWh/kg	-	0.46	0.44	0.44	0.44	0.46
MCH	Cold duty	kW	-	268.47	251.95	251.17	253.86	261.74
	UA	MW/°C	-	26.55	21.47	21.23	20.47	19.17
	LMTD	°C	-	10.11	11.74	11.83	12.40	13.65
	ΔT_{min}	°C	-	3.52	3.24	3.43	4.80	8.36
TCI		k$	2032.69	4509.45	4421.16	4413.08	4370.17	4467.56
ATCI	Compressor	k$/yr	234.16	421.75	414.34	413.74	409.84	422.19
	LT	k$/yr	-	-	3.98	3.97	3.99	4.26
	CHE	k$/yr	-	75.31	68.77	68.45	67.45	65.69
	Intercooler	k$/yr	4.60	16.93	16.53	16.50	16.35	16.92
	Separator	k$/yr	-	15.69	15.69	15.69	15.69	15.69
	Total	k$/yr	238.76	529.68	519.31	518.36	513.32	524.76
ATOC	Other[c]	k$/yr	134.16	297.63	289.56	289.03	289.19	311.57
	Net power	k$/yr	226.06	485.39	470.05	469.14	463.09	482.05
	Intercooler	k$/yr	2.10	6.86	6.65	6.64	6.56	6.85
	Total	k$/yr	362.31	789.87	766.27	764.81	758.84	800.47
BOG loss		k$/yr	948.69	78.83	78.83	78.83	78.83	78.83
TAC		k$/yr	1549.76	1398.38	1364.41	1362.00	1350.99	1404.06
Relative payback period[d]		yr	-	5.60	5.13	5.09	4.94	5.64

[a]Liquid fraction of the phase separator inlet stream.

[b]The fraction of the total compression power related to recycled BOG mass flow rate divided by the final liquid product entering the storage tank.

[c]The fixed cost, the maintenance cost and the cost for supplies.

[d]Payback period relative to the reference system = $(\mathrm{TCI} - \mathrm{TCI}_{\mathrm{ref}})/(\mathrm{ATOC} + \mathrm{BOG\ loss})_{\mathrm{ref}} - (\mathrm{ATOC} + \mathrm{BOG\ loss})$.

Regarding the configurations with BOG liquefaction, the systems with an LT require less TAC than the JT processes except for the HP mix LT-JT process. The addition of the turbo-machinery to the JT system (the LT-JT process) results in 2.4 % savings in the TAC. The reduction in TAC comes mostly from reduced compression power and reduced heat exchanger cold duty. As seen in Table 8, the liquefaction systems with an LT have a higher liquefaction ratio than the systems using JT valves only. This high liquefaction ratio leads to a smaller flow rate of the vapor product in the phase separator, which is mixed with the BOG from the storage tank. The reduction in flow rate of the process feed stream results in smaller duties for all the equipment in the systems, thus decreasing the ATCI and the ATOC. The small power production from the LT also helps to decrease the operating cost.

It is noticeable that the processes with an LT have increased LMTD values in the CHE compared to the JT system. Although the increase in the LMTD value causes larger entropy generation and lower thermodynamic efficiency of the system, it decreases the UA value and the capital cost of the exchanger. In summary, the LT based liquefaction facilities have lower or equal specific power consumption of BOG reliquefaction compared to the JT processes, indicating that they are able to improve the process thermodynamic efficiency, even with an increased LMTD value. Therefore, the liquefaction systems with an LT result in better trade-off points where the benefit from decreasing the UA value is larger than the penalty of the increased LMTD value.

Regarding the variations of the LT based systems, the LP mix LT-JT configuration shows a marginal decrease in TAC compared to the LT-JT process. The mixing of the BOG from the tank and the vapor product from the phase separator increases entropy generation in the mixer (MIX-1) due to the large temperature difference of the streams. In contrast, the LP mix LT-JT system mixes the two cold streams after they pass through the CHE. The mixing at the CHE outlet decreases the entropy generation in the mixer as the streams have almost the same temperature. Although the economic improvement is minor, the smaller entropy generation reduces the compressor work.

The IP mix LT-JT system also shows some savings in the TAC compared to the LT-JT process. As mentioned in Section 2.3, the vapor stream from the phase separator by-passes the first stage compressor and intercooler and is supplied to the second compressor. This simple modification leads to a reduction in the duty of the compressor and the intercooler. Thus, these units have the smallest capital cost compared to other system options.

In contrast to other LT based processes, the HP mix LT-JT system has a larger TAC than the LT-JT system. As seen in Table 7, the optimization results of the high pressure mixing configuration indicate that it has a throttling pressure of 12 bar. This high depressurization pressure results in a phase separator with marginal vapor product, as it can be observed by the liquefaction ratio of 0.97 for the HP mix LT-JT system in Table 8. As a result, this system eventually has almost the same characteristics as the LT-JT process without the vapor stream from the phase separator. Thus, the optimization work performed for the HP mix LT-JT system is similar to the work done for the LT-JT process, however with a reduced lower bound for the throttling pressure, which is constrained to the discharge pressure of the second compressor. The limited bound of the outlet pressure of the JT valve (VLV-1) leads to sub-optimal solutions for the configuration, resulting in larger TACs with higher specific power consumption for LNG production in the HP mix LT-JT system (see Table 8).

The configurations used in the LP and IP mix LT-JT systems are also advantageous even when the liquid turbine is unavailable as seen in Table 9. Without the LT, the LP and IP mix configurations can achieve some savings in TAC compared to the basic JT system. In addition, the IP mix JT process even has a TAC and payback period close to the LT-JT system. Therefore, the IP mix JT configuration is a promising alternative to BOG liquefaction systems with an LT if the reliability of the turbo-machinery is not sufficiently high.

Table 9. The optimization result of the LP, IP and HP mix JT processes.

Parameter	Unit	JT	LT-JT	LP mix JT	IP mix JT	HP mix JT
TAC	k$/yr	1398.38	1364.41	1395.72	1379.15	1428.21
Relative payback period	yr	5.60	5.13	5.56	5.31	6.01

5.2 Sensitivity analysis

LNG price is an important parameter when evaluating the economics of the fuel supply systems for LNG vessels. The price is directly linked to the BOG burned in the GCU as a loss of the cargo. To measure the effect on the process, sensitivity analysis is performed with varying LNG price from 2 to 8 (USD/MMBtu). Not surprisingly, Figure 6 indicates that the TAC of the reference system increases with the LNG price. The configuration and operating conditions of the reference process are not affected by the price during optimization, and the TAC is changed only due to the economic loss of the BOG wasted in the GCU. Detailed cost evaluation based on the LNG price is listed in Table S1 in Appendix A. Thus, the economics of the reference fuel supply system is sensitive to the LNG price as the process always burns a significant amount of BOG all the time. If the LNG price increases from 2 to 8 USD/MMBtu, the TAC of the reference system is more than doubled.

In contrast, the fuel supply systems with BOG liquefaction are less sensitive to the LNG price as illustrated in Figure 6. All the liquefaction schemes show some increase in their TAC from 2 to 4 USD/MMBtu. However, they only have marginal increase in the TAC from 4 to 8 USD/MMBtu. As indicated in Table 10, the optimization results for LNG prices equal to or greater than 4 USD/MMBtu show that the liquefaction facilities have been optimized to have almost no BOG burned in the GCU. Thus, BOG losses only occur during unloading, which is the reason for the minor increase in the TAC from 4 to 8 USD/MMBtu.

For LNG prices below 4 USD/MMBtu, all the liquefaction processes increase the amount of BOG wasted in the GCU with decreasing LNG price, as seen in Table 10. The increase in the burned BOG results in reduced liquefaction requirements in the systems (i.e. smaller LNG production from BOG). Thus, when the LNG price is below 4 USD/MMBtu, the configurations with BOG liquefaction are optimized to considerably reduce LNG production, since the economic benefit from smaller equipment sizes related to reduced liquefaction demand overcomes the cost of larger BOG losses. Therefore, if the LNG price is below 4 USD/MMBtu, liquefaction of BOG is less attractive than simply burning it, at least from an economic point of view.

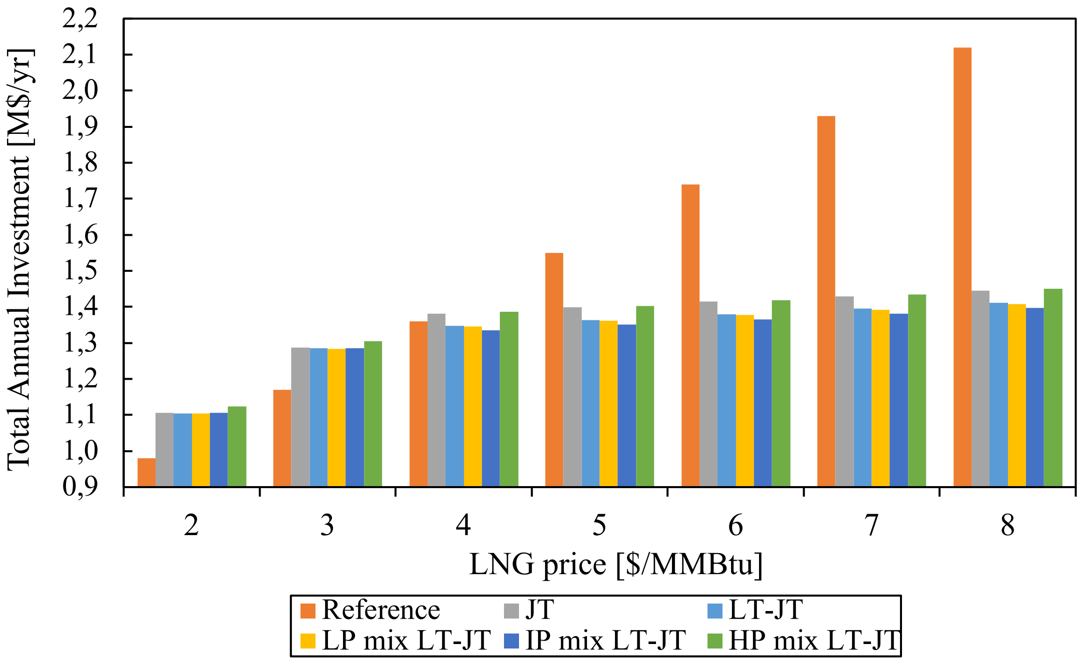

Figure 6. Total annual cost as function of LNG price

It should also be noticed that although the optimization of all configurations with BOG liquefaction systems try to decrease the TAC by minimizing the LNG production for LNG prices below 4 USD/MMBtu, they all have higher annual cost compared to the reference system. The larger number of units is the main reason for the higher TAC. Even though the capacity of the units is minimized, the fixed charge term of the purchased cost (coefficient K1 in Eq. (6)) adds considerably to the total investment cost. Other equipment related costs such as maintenance and supplies will also contribute to the larger TAC.

For LNG prices above 4 USD/MMBtu, the fuel supply systems with BOG liquefaction will have lower total annual cost than the reference process. The LT based systems, except for the HP mix configuration, will be more economical than the reference process from slightly below 4 USD/MMBtu. Other liquefaction schemes are profitable compared to the reference system when the LNG price is above 4 USD/MMBtu. The higher TAC of the reference process than the configurations with BOG liquefaction are mainly caused by the increase in BOG losses, which are proportional to the LNG price. Therefore, there are economic benefits from liquefaction facilities on LNG carriers when the LNG price is higher than 4 USD/MMBtu.

Among the fuel supply systems with BOG liquefaction, the IP mix LT-JT configuration is the most economic to be used on LNG ships when the LNG price is higher than 4 USD/MMBtu, and it is followed by the LP mix LT-JT and the LT-JT configurations. The JT and the HP mix LT-JT systems have similar TACs, which are larger than the other LT based processes. This is the same trend as observed with a fixed LNG price of 5 USD/MMBtu in Section 5.1. However, if the LNG price drops to 2 or 3 USD/MMBtu, all configurations with liquefaction facilities have almost identical TACs except for the HP mix LT-JT system. The minimized LNG production and reduced equipment sizes in the processes weaken the characteristics of each configuration. In the case of the HP mix LT-JT process, the restricted throttling pressure causes sub-optimal operating conditions, giving a larger TAC than for other liquefaction systems.

Table 10. Mass flow rates of the LNG product and the BOG sent to the GCU for different LNG prices.

LNG price [$/MMBtu]	Reference		JT		LT-JT		LP mix LT-JT		IP mix LT-JT		HP mix LT-JT	
	$\dot{m}_{\mathrm{LNG}}$	$\dot{m}_{\mathrm{GCU}}$	$\dot{m}_{\mathrm{LNG}}$	$\dot{m}_{\mathrm{GCU}}$	$\dot{m}_{\mathrm{LNG}}$	$\dot{m}_{\mathrm{GCU}}$	$\dot{m}_{\mathrm{LNG}}$	$\dot{m}_{\mathrm{GCU}}$	$\dot{m}_{\mathrm{LNG}}$	$\dot{m}_{\mathrm{GCU}}$	$\dot{m}_{\mathrm{LNG}}$	$\dot{m}_{\mathrm{GCU}}$
2	0	1070	40	1030	45	1025	45	1025	45	1025	43	1027
3	0	1070	63	1007	73	997	75	995	83	987	69	1001
4	0	1070	1015	55	1064	0	1064	0	1063	0	1063	0
5	0	1070	1063	0	1064	0	1064	0	1063	0	1063	0
6	0	1070	1063	0	1064	0	1064	0	1063	0	1063	0
7	0	1070	1063	0	1064	0	1064	0	1063	0	1063	0
8	0	1070	1063	0	1064	0	1064	0	1063	0	1063	0

6. Conclusion

For an LNG vessel propelled by the high pressure gas injection engines, a reference fuel supply system and its variations with BOG liquefaction based on the Joule-Thomson (JT) cycle were optimized and compared. Total annual cost was selected as the objective function for the optimization in order to evaluate the economic benefit of the additional liquefaction facilities compared to the reference system.

With an LNG price of 5 USD/MMBtu, the optimization results indicate that the reliquefaction systems employed on the vessel improve the economics of the LNG carrier with lower TAC values than the reference configuration, saving at least 9.4 % of the TAC. The relatively simple structure of the liquefaction processes results in marginal increase in capital cost while minimizing cargo loss, making the additional facilities economically profitable on LNG carriers. The use of a liquid turbine (LT) and the simple structure modifications lead to an even smaller TAC value of the liquefaction systems.

The sensitivity analysis with different LNG prices indicates that the installation of the liquefaction systems on LNG carriers is profitable compared to the reference process when the LNG price is above 4 USD/MMBtu. With an LNG price of 8 USD/MMBtu, the reference fuel supply system has a TAC that is 46% higher than the liquefaction processes, due to the high cost of BOG loss in the GCU.

However, if the LNG price is below 4 USD/MMBtu, the reference fuel supply system will be superior to the configurations with BOG liquefaction since the BOG losses have a small impact on the economics of the LNG vessel compared to the additional capital investment, which is the major concern of the liquefaction systems. In conclusion, the optimal design of the fuel supply system for LNG carriers will be dependent on the LNG price.

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Nomenclature

Roman letters

$ATCI$ = annual total capital investment [$/yr]

ATOC = annual total operating cost [$/yr]

C = annual cost [$/yr]

D = duty [kW]

E = Energy value of burned BOG [kJ/d]

F = factor [-]

i = interest rate [%]

LHV = lower heating value [kJ/kg]

Lv = liquid level [%]

MMBtu = million British thermal units [-]

$\dot{m}$ = mass flow rate [kg/h]

N = number of cycles [cycle/yr]

n = service life of LNG vessels [yr]

P = power [kW]

Pr = pressure ratio [-]

p = pressure [bar]

r = rate [%/d]

$SFOC$ = specific fuel oil consumption [kJ/kWh]

T = temperature [K]

t = duration [d/cycle]

TAC = total annual cost [$/yr]

TCI = total capital investment [$/yr]

USD = United States dollar

V = volume [m^3]

v = unit price [$/kJ, $/kW]

x = fraction [-]

Greek letters

Δp = pressure drop [bar]

ΔT_{min} = minimum approach temperature [°C]

ρ = density [kg/m^3]

Subscripts and superscripts

BM = bare module costs

BOG = boil-off gas

BOG loss = boil-off gas burned in GCU

BOR = boil-off rate

comp = compressor

CTO = correlation from capital cost to operating cost

CW = cooling water

cycle = voyage cycle

engine = DFDE or propulsion engine

Ext = extra expenses

fuel = fuel for the DFDE or propulsion engine

GCU = gas combustion unit

j = process unit

LNG = liquefied natural gas

LT =liquid turbine

out =outlet stream

P = purchased cost

ref = reference fuel supply system

tank = LNG storage tanks

vap = vapor

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://

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