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Thermoeconomic Simulation of Marine Energy Systems for a Liquefied Natural Gas Carrier

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Abstract

The recent increase in marine transportation of Liquefied Natural Gas (LNG) made the design of modern LNG vessels more demanding in terms of both increased cargo capacity and fuel economy. A detailed thermoeconomic model of the energy system of a LNG vessel is developed in this study. The model addresses both the energy system components and the production of boil-off gas, which is the main fuel of these vessels. A generic energy system that comprises various technology and configuration options is developed. In addition, a realistic operating profile of a LNG vessel is considered. The thermoeconomic model is subsequently used for synthesis, design and operation optimization of the system.

Keywords: LNG carrier, thermoeconomic model, boil-off gas, energy system

1. INTRODUCTION

The dominant role of natural gas as a primary fuel in the global energy sector has intensified the need for seaborne transportation of this fuel. Marine transport of natural gas is predominately in the form of Liquefied Natural Gas (LNG) carried by special vessels (LNG carriers) equipped with cryogenic tanks.

Due to the recent global fuel market developments, the continuously rising environmental concerns and the existence of many natural gas reservoirs in areas where the construction of a land gas pipeline is not feasible, the LNG shipping sector is continuously growing. Therefore, the need of efficient and economic propulsion of LNG vessels is important for the viability of the marine LNG transport sector.

A thermoeconomic generic model of the energy system of a LNG vessel has been developed, suitable for use in optimization studies. The complete analysis, modelling approach and developed simulation model are presented in this study. The thermoeconomic model is combined with a dynamic model of the boil-off of LNG during voyage, which describes the effect of the variations of boil-off gas (BOG) quantity and quality in time. This dynamic model is described in a separate paper (Dimopoulos and Frangopoulos, 2008a). The thermoeconomic generic model has been subsequently used for the synthesis, design and operation optimization of the energy system of a LNG vessel, as it is described in an accompanying paper (Dimopoulos and Frangopoulos 2008b).

2. DESCRIPTION OF THE LNG MARINE ENERGY SYSTEM

2.1 LNG Vessels and shipping

LNG is stored onboard vessels in cryogenic tanks, at very low temperatures (about -163°C). LNG vessels are not equipped with refrigeration plants and the natural gas is kept in liquid form by the thick insulation of their cryogenic cargo tanks. However, a fraction of the cargo LNG volume evaporates during voyage, which is usually called Boil-Off Gas (BOG). One particular characteristic of LNG carriers is that they usually use BOG as a fuel for their propulsion plant. A common solution for propulsion of LNG carriers during the past decades was the boiler – steam turbine propulsion plant (Andrianos, 2006).

The continuing growth of LNG marine transportation has caused a rapid increase in new orders for LNG vessels (Naval-Architect, 2005). The renewed interest in LNG shipping in present time, leads to the investigation of a variety of propulsion options for modern LNG carriers (Andrianos, 2006; Hansen and Lysebo, 2004; Levander and Hannula, 2004; MAN-B&W, 2004; Naval-Architect, 2005). In addition, modern LNG carriers are designed for increased cargo capacities (ranging from 150000 to 220000

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m^3) and high speed ranges (17 – 25 knots). Therefore, the power requirements of such vessels are considerably higher than in the past.

2.2 Generic System

An integrated energy system of a LNG vessel has been considered. The principal energy demands of modern LNG vessels are propulsion power, electricity for covering the hotel and auxiliary systems related loads and heat in the form of water or low pressure steam for heat driven auxiliary equipment and sanitary purposes. An attractive option for these ships is the integrated energy system, which consists of electricity producing units (e.g. gas turbine generators), exhaust gas boilers, steam turbine(s) and electric propulsion motors. This configuration has several advantages in terms of flexibility, reduced space requirements and efficiency, compared with the mechanically driven propulsors and the independent generating sets for auxiliary loads (Andrianos, 2006; Hansen and Lysebo, 2004). Combined cycle plants, in particular, are of increased interest recently due to their high total efficiency.

The generic model consists of gas turbines (GT), heat recovery steam generators (HRSG) and steam turbines (ST) supplying the ship with electricity and heat. These systems are usually referred to as COGES (Combined Gas turbine Electric and Steam turbine) in the marine industry. A similar COGES system has also been investigated for a cruise vessel (Dimopoulos et al., 2006).

The system under study produces electricity and low pressure (LP) superheated steam. The generic configuration (super-configuration) consists of:

- A number of identical high power output gas turbines (type A).
- A number of identical gas turbines of moderate output (type B).
- A number of HRSGs with various connection options with the gas turbines. HRSGs can be either single or dual pressure. The quality of the high pressure (HP) superheated steam can be varied by adjusting the pressure and temperature.
- A steam turbine driven by high pressure steam.

Furthermore, the system has the following operating features:

- The load of each GT can be varied independently.
- There is an exhaust gas by-pass in each HRSG that can regulate the amount of exhaust gases supplied to the unit.
- When a dual pressure boiler is present in the configuration, the fraction of the total steam supplied as LP steam can be varied by means of a regulating valve.
- There is a throttling valve between the HP and LP steam lines. The fraction of HP steam throttled to LP can be varied.
- The steam turbine has an extraction point to supply LP steam. The extracted mass flow rate can also be regulated.

The generic COGES system is graphically depicted in *Figure 1*, while the single and dual pressure HRSGs are depicted in *Figure 2*. The independent optimization variables, used in the problem presented in the accompanying paper (Dimopoulos and Frangopoulos, 2008b), appear also in these figures. It is worth noting that this generic system encompasses many synthesis, design and operation options and therefore it is particularly useful for optimization studies. The mathematical formulation of the pertinent simulation models is described in Sections 3 and 4.

3. BOIL–OFF GAS MODEL

The handling of the boil-off gas during the LNG vessel operation is a key issue in the technical and economic assessment of the complete energy system. According to the type of the energy system, BOG can be used as fuel, reliquefied or burned in a gasification unit.

In a gas turbine based propulsion system, BOG is used as a primary fuel. Whenever the BOG from natural evaporation is not sufficient to cover the energy needs of the system, forced evaporation of LNG is applied. If the use of BOG is prohibited due to safety precautions or there is not sufficient quantity of LNG onboard to be evaporated, then the GT units can operate with Marine Gas Oil (MGO).

In order to assess the variation of BOG quantity and quality (lower heating value) during voyage, a detailed dynamic boil-off model has been used, which is described in detail in (Dimopoulos and Frangopoulos, 2008a). This model accounts for the variation of BOG mass flow, composition and thermodynamic properties during voyage. The model employs vapor-liquid equilibrium calculations of the LNG mixture coupled with dynamic species conservation over time.

The use of this model allows for a detailed assessment of the effect of the varying BOG quantity and quality to the overall thermoeconomic model of the marine energy system. Preliminary results indicated that this variation significantly affects the overall performance of the overall energy system and therefore it should be taken into account.

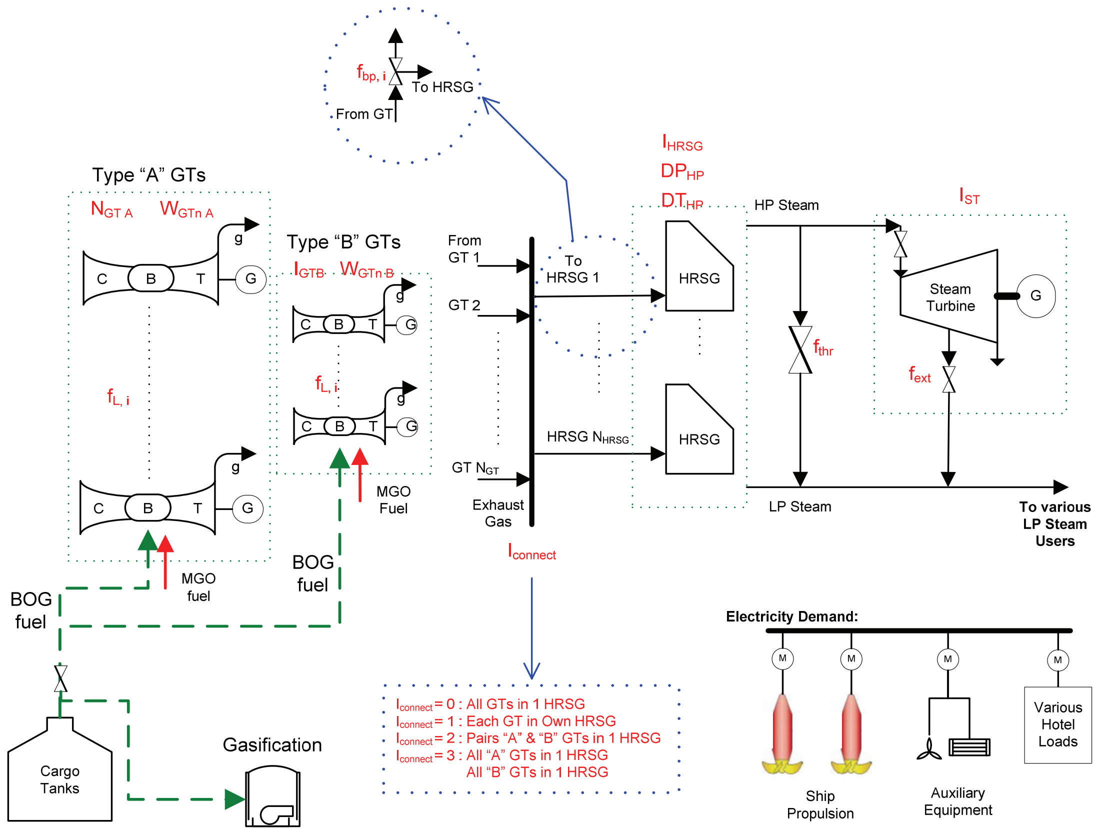

Figure 1. The generic COGES system of a LNG carrier.

4. THERMOECONOMIC MODEL OF THE MARINE ENERGY SYSTEM

4.1 Simulation Models

The model developed in (Frangopoulos and Dimopoulos, 2004) has been extended for the performance simulation of marine gas turbine units. For each gas turbine two sets of equations, one for nominal and another for off design performance, have been employed:

$$Y_{n\,GT} = f_n\left(\dot{W}_n\right)_{GT} \tag{1}$$

$$Y_{GT} = f\left[\left(\dot{W}_n, f_L\right)_{GT}, T_a\right] \tag{2}$$

where Y is one of the following: η, $\dot{m}_g$, T_g .

In this study, two types of boiler technology for the HRSG units have been considered: a) single pressure and b) dual pressure. A schematic layout of these technologies is depicted in *Figure 2.*

The modelling approach followed in Chin and El-Masri (1987), Frangopoulos and Dimopoulos (2004) and Kougioufas (2005) has been used for the nominal performance simulation of these units. The general functional form of the nominal thermodynamic simulation model of a HRSG is:

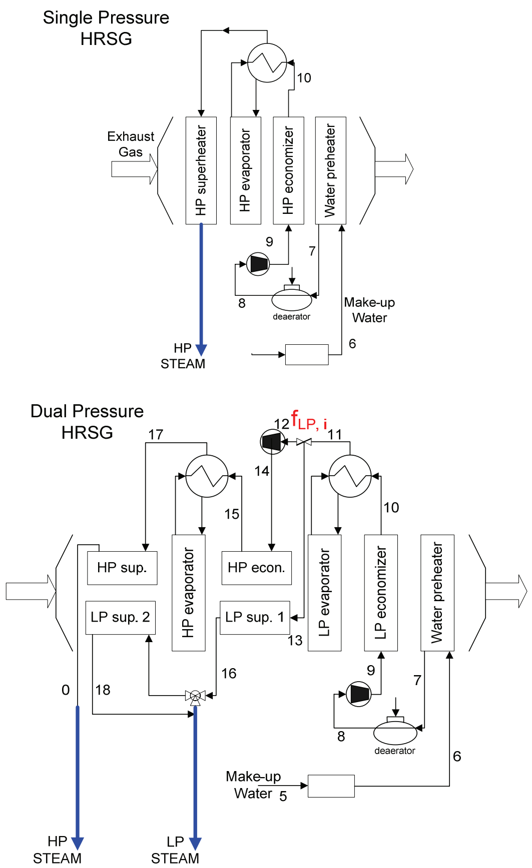

Figure 2. Unit configurations for single and dual pressure HRSG.

$$Y_{HRSG} = f\begin{bmatrix}(\dot{m}_g, T_g)_{HRSG} \\ (P,T)_{HP} \\ (P,T)_{LP}\end{bmatrix} \quad (3)$$

where Y_{HRSG} is one of the following: $\dot{m}_{HP}$, $\dot{Q}_{HP}$, $\dot{m}_{LP}$, $\dot{Q}_{LP}$, $\dot{W}_{aux}$. The exhaust gas flow and temperature at the inlet of each HRSG is a function of the number and performance characteristics of GT units connected to HRSG. Equation (3) is used for sizing of each HRSG unit. In terms of sizing, each heat exchanging area is evaluated subject to constraints of minimum permissible pinch point temperature differences.

The form of the off-design simulation model used for HRSG operation is similar to Equation (3). The main difference of this model is that the heat transfer coefficients in the HRSG heat exchangers are varied with respect to exhaust gas flow and temperature, with a relation of the form (Olsommer, 1998):

$$\frac{U}{U_n} = f\left(\frac{\dot{m}_g}{\dot{m}_{gn}}, \frac{T_g}{T_{gn}}\right) \quad (4)$$

With this approach, the operation HRSG simulation model is solved iteratively by keeping the heat exchanger areas constant (to the value found in nominal – sizing simulation) and determining the operating pinch point temperature differences (Olsommer, 1998). For the dual pressure boiler simulation, the fraction of the total steam supplied as LP steam is an additional input to the model.

It must be noted that for the single pressure model, the terms in Equation (3) with index “LP” do not appear.

The steam turbine model has been developed in Kougioufas (2005) using data in tables and graphs of SNAME (1973), according to the method and data of the Society of Naval Architects and Marine Engineers (SNAME). The model consists of two sets of nonlinear equations: one for nominal and another for off-design performance.

$$f\left(\dot{m}_{ST_n}, P_{HP}, T_{HP}, \eta_{ST_n}, \dot{W}_{ST_n}\right) = 0 \quad (5)$$

$$f\begin{pmatrix}\dot{m}_{ST}, f_{ext}, P_{HP}, T_{HP}, \eta_{ST_n}, \dot{W}_{ST_n}, \\ \eta_{ST}, \dot{W}_{ST}\end{pmatrix} = 0 \quad (6)$$

The overall simulation model is complemented by overall mass and energy balances. The HP steam mass flow rate to the steam turbine is determined by:

$$\dot{m}_{ST} = (1 - f_{thr}) \cdot \sum_{i=1}^{n_{HRSG}} \dot{m}_{HP_i} \quad (7)$$

while the extracted mass from the steam turbine is:

$$\dot{m}_{ext} = f_{ext} \cdot \dot{m}_{ST} \quad (8)$$

The total LP steam mass flow rate produced by the system is:

$$\dot{m}_{LP_{Pr}} = f_{thr} \cdot \sum_{i=1}^{n_{HRSG}} \dot{m}_{HP_i} + \dot{m}_{ext} + \sum_{i=1}^{n_{HRSG}} \dot{m}_{LP_i} \quad (9)$$

The net electric power produced by the COGES system is:

$$\dot{W}_{net} = \sum_{i=1}^{n_{GT}} \dot{W}_{GT_i} + \dot{W}_{ST} - \dot{W}_{aux} \quad (10)$$

The total BOG fuel consumption is determined by adding the natural boil-off with the forced boil-off mass flow rate (if any). Forced boil-off of LNG occurs only when the natural BOG is not sufficient to cover the GT fuel demand.

$$\dot{m}_{BOG_{tot}} = \dot{m}_{BOG_{nat}} + \dot{m}_{BOG_{frc}} \quad (11)$$

Finally, it is worth noting, that in case of an excess of BOG, the surplus is burned and released to the atmosphere in a gasification unit. This is due to the fact that the existence of a reliquification unit onboard LNG vessels that use BOG as primary fuel, is not economically viable under the current conditions (Andrianos, 2006). In addition, the existence of a gasification unit onboard LNG carriers is required by international maritime regulations.

4.2 Cost Models

The capital cost of a marine gas turbine unit is expressed as a function of the nominal electric output derived by regression analysis of market data (GTW, 2003) and (Frangopoulos and Dimopoulos, 2004)

$$C_{C_{GT}} = \left[c_1 \cdot \left(\dot{W}_{GTn}\right)^{c_2}\right] \cdot \dot{W}_{GTn} \quad (12)$$

where c_1 = 1970.17 and c_2 = –0.18, are statistically derived constants.

The same methodology has been applied for the capital cost of the steam turbine using market data from GTW (2003) and a cost function expression appearing in Pelster (1998)

$$C_{C_{ST}} = \left[c_{ref}\left(\frac{\dot{W}_{ST_n}}{\dot{W}_{ref}}\right)^a\right] \cdot \dot{W}_{ST_n} \quad (13)$$

where a = –0.67 is a statistically derived constant, and c_{ref} = 300 US\$/kW and $\dot{W}_{ref} = 15000$ kW unit cost and nominal power of a reference ST unit.

The cost function appearing in Pelster (1998) and Frangopoulos (1994) has been used for the capital cost of the HRSG units, with its coefficients adapted according to data found in GTW (2003):

$$C_{C_{HRSG}} = c_1 \sum_i \left(f_{p_i} \cdot f_{T_{i,ST}} \cdot f_{T_{i,g}} \cdot \left(\frac{\dot{Q}_i}{\Delta T_{ln_i}} \right)^{0.8} \right)_i \quad (14)$$
$$+ c_2 \sum_j f_{p_j} \cdot \dot{m}_{ST_j} + c_3 \cdot \dot{m}^{1.2}_{HRSG_g}$$

where f_{p_i}, $f_{T_{i,ST}}$, $f_{T_{i,g}}$ and f_{p_j} are pressure and temperature correction factors for both gas and steam sides of the heat exchangers of the HRSG, and c_1, c_2 and c_3 are statistically derived cost coefficients.

5. VOYAGE ANALYSIS

5.1 Typical voyage characteristics

Following the typical marine design practice, the voyage profile of a LNG vessel has been decomposed into five characteristic phases (Andrianos, 2006; Levander and Hannula, 2004; MAN-B&W, 2004):

1. Voyage in full load condition from the loading to the off-loading terminal (port).
2. Voyage in ballast condition from the off-loading to the loading terminal.
3. Manoeuvring during approach to both the loading and off-loading terminals.
4. LNG loading period in the loading terminal.
5. LNG delivery period in the off-loading terminal.

These five phases constitute the so-called round trip of a LNG vessel.

The following characteristics are worth noting (Andrianos, 2006; Levander and Hannula, 2004; MAN-B&W, 2004):

- The vessel sails in phases 1 and 2 with the same speed, called service speed (V_S).
- In phases 3, 4 and 5, operation with boil-off gas is prohibited due to safety precautions. The fuel used in these phases is MGO.
- Loading of LNG is performed by shore based cryogenic pumps, while off-loading is performed by the vessel's onboard cargo pumps. Hence the power needs in phase 5 are higher than those of phase 4.
- A significant fraction of the LNG cargo volume (about 5%) cannot be practically off-loaded. This is usually called the heel volume. Therefore, a fraction of this amount of LNG is evaporated during ballast voyage and is used as BOG fuel. The heel volume is also used to keep cargo tanks cool during the ballast voyage.

5.2 Energy Demands

The needs of a LNG carrier in electrical and thermal energy are functions of the aforementioned round-trip phases and the service speed of the vessel. Based on a detailed study of energy needs in Andrianos (2006) and additional data from Hansen and Lysebo (2004), Levander and Hannula (2004), and MAN-B&W (2004), the power demands in each phase for a range of service speeds for a LNG vessel of 150000 m^3 capacity are determined and presented in Table 1.

The time duration for each one of the phases 3, 4 and 5 is considered fixed, while for the main parts of the round-trip (i.e. phases 1 and 2) the duration is a function of the sailing distance and the speed of the vessel.

TABLE 1. DEMAND OF ELECTRICITY AND HEAT IN EACH OPERATING MODE AND FOR VARIOUS DESIGN SERVICE SPEEDS.

Phase	V_S [kn]	$\dot{W}_{D_{prop}}$ [kW]	$\dot{W}_{D_{aux}}$ [kW]	$\dot{m}_{D_{LP}}$ [kg/s]
1. Full Load Duration: $f(S/V_S)$	17	16600	1300	0.50
	19	24200	1500	0.65
	21	34800	1700	0.80
	23	52400	2200	0.95
	25	79500	2800	1.10
2. Ballast Duration: $f(S/V_S)$	17	15770	1170	0.50
	19	22990	1350	0.65
	21	33060	1530	0.80
	23	49780	1980	0.95
	25	75525	2520	1.10
3. Mnvr. @ 5kn Duration: 12 h	17	3758	1040	0.50
	19	4293	1200	0.50
	21	4983	1360	0.50
	23	6101	1760	0.50
	25	7724	2240	0.50
4. Loading Duration: 18 h		0	5100	0.25
5. Off-load. Duration: 18 h		0	12000	0.70

6. ECONOMIC ANALYSIS

In order to assess the economic viability of the generic COGES system, a detailed economic analysis has been performed. LNG vessels are long time chartered or owned by oil and gas or energy producing companies. The chartering or service agreements are usually long term (20 years or more).

The charterer buys the LNG at a certain FOB price or, in the case of an oil producing company, LNG is produced at certain FOB costs at the export terminal. LNG is sold at the import terminal at a higher CIF price. The profit from the LNG marine transportation is the difference between the delivered LNG at CIF price and the loaded LNG cargo at FOB price (Tolgos, 2006).

It is considered that the operating expenses of a LNG vessel per round trip consist of fuel and maintenance costs of the energy system components, port fees on each port approach and the LNG FOB costs. Taking into account each one of the various phases of a round trip, the following equation is derived:

$$C_{op,rnd} = 2\cdot C_{port} + \left(FOB\cdot \rho_{LNG}\cdot V_{tot}\right) + \\ +\sum_{k=1}^{5}\left[C_{LNG} + C_{MGO} + C_{m}\right]\cdot \Delta\tau_k \quad (15)$$

The duration $\Delta\tau_k$ for k = 3, 4, 5 is fixed (see Table 1). For the full load and ballast voyage, the durations are:

$$\Delta\tau_1 = \Delta\tau_2 = \frac{S}{V_S} \quad (16)$$

The operating income of the LNG vessel is a function of the delivered volume of the gas at CIF price. The delivered LNG volume is:

$$V_{Delivered} = \left(1 - r_H\right)\cdot\left(V_{tot} - V_{BOG}\right) \quad (17)$$

The volume of BOG consists of both the natural and forced boil-off. It is noted that the heel fraction that cannot be unloaded is also taken into consideration in Equation (17).

The round-trip profit of the system is:

$$F_{rnd} = CIF\cdot V_{Delivered} - C_{op} \quad (18)$$

The average number of round-trips per year can be readily calculated:

$$n_{rnd} = \frac{8760\ {}^{h}\!/_{year}}{\sum_{t=1}^{5}\Delta\tau_t} \quad (19)$$

Therefore the yearly costs and profit are:

$$C_{op} = C_{op,rnd}\cdot n_{rnd} \\ F = F_{rnd}\cdot n_{rnd} \quad (20)$$

7. OPTIMIZATION OF THE COGES SYSTEM

As a case study, the synthesis, design and operation optimization of a COGES system for a LNG vessel is performed. The formulation of the optimization problem, the solution method and the results are presented in detail in an accompanying paper (Dimopoulos and Frangopoulos, 2008b).

The LNG carrier has a capacity of 150000 m^3, with electricity and thermal power needs presented in Table 1. Additional data for the problem are presented in the accompanying papers (Dimopoulos and Frangopoulos, 2008a; Dimopoulos and Frangopoulos, 2008b).

8. CONCLUSIONS

A thermoeconomic generic simulation model for the energy system of LNG vessels is proposed. A model for the production of boil-off gas has been developed and incorporated in the generic model. The simulation models of the individual components have been developed for both design and off-design conditions. In this study, many of the simplifying assumptions usually made in the design of LNG propulsion systems have been replaced by detailed modelling. The developed model is suitable and has been used for synthesis, design and operation optimization studies.

NOMENCLATURE

BOG	Boil-off Gas
C	Cost [US $]
c	Unit cost [US $/kg or US $/kWh]
CIF	Cost–Insurance–Freight LNG price [$/kg or $/mmBTU]
F	Profit [$]
f	Fraction, factor, function
f_L	Load factor
FOB	Free–On–Board LNG price [US $/kg or US $/mmBTU]
LNG	Liquefied Natural Gas
$\dot{m}$	Mass flow rate [kg/s]
MGO	Marine Gas Oil
n	Number of components
P	Pressure [bar]
$\dot{Q}$	Thermal power [kW]
r_H	Heel volume fraction [%]
S	Sailing distance [nm]
T	Temperature [K or ^{o}C]
U	Heat transfer coefficient [kW/m^2 K]
V	Volume [m^3]
V_S	Vessel service speed [kn]
$\dot{W}$	Electric power [kW]

Greek Letters

$\Delta\tau$	Duration of time interval [h]
η	Efficiency

Subscripts

a	ambient
aux	Auxiliary
C	Capital
D	Demand
ext	Extraction
g	Gas
GT	Gas turbine
frc	Forced
HRSG	Heat recovery steam generator
HP	High pressure
ln	Logarithmic
LP	Low pressure
m	Maintenance
n	Nominal
nat	Natural

net	Net
port	Port fees
prop	Propulsion
rnd	Round-trip
ST	Steam turbine
thr	Throttling
tot	Total
V	Cargo tank

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