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Case Study on Boil-Off Gas (BOG) Minimization for LNG Bunkering Vessel Using Energy Storage System (ESS)

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Abstract: Liquefied natural gas (LNG) is recognized as a preferable alternative fuel for ship owners, since it can substantially reduce harmful emissions to comply with stricter environmental regulations. The increasing number of LNG-fueled vessels has driven up the number of LNG bunkering vessels (LNGBVs) as well. A key issue of LNGBVs is boil-off gas (BOG) generation, especially the huge amount of BOG that is generated during loading and unloading (bunkering) processes. This study proposes a hybrid system that combines conventional onboard LNG-fueled generators with an energy storage system (ESS) to solve the BOG issue of LNGBVs. This hybrid system is targeted at an LNGBV with the cargo capacity of 5000 m^3. The amount of BOG generation is calculated based on assumed operation modes, and the economic study and the environmental analysis are performed based on the results. By comparing the conventional system to the proposed ones, some benefits can be verified: about 46.2% BOG reduction, 66.0% fuel saving, a 7.6-year payback period, and 4.8 tons of greenhouse gas (GHG) reduction for one voyage in the best case, with some assumptions. This proposed hybrid system using the ESS could be an attractive green solution to LNGBV owners.

Keywords: LNG bunkering vessel (LNGBV); LNG-fueled vessel; boil-off gas (BOG); energy storage system (ESS); battery; greenhouse gas (GHG); hybrid system

1. Introduction

The air pollutant emissions from ships have increased over the last 50 years, and these have had negative impacts on the marine environment and human health [1]. In order to participate in global efforts to reduce harmful emissions, in April 2018, the International Maritime Organization (IMO) adopted an initial strategy to reduce the total annual greenhouse gas (GHG) emissions at least 50% by 2050 compared to 2008 [2].

With increasing pressure to reduce emissions from ships, the liquefied natural gas (LNG) is recognized as an attractive solution in the marine industry. The utilization of LNG as a marine fuel is an attractive option, because it can remove sulfur oxides (SO$_X$) and particulate matter (PM) emissions completely, and it can reduce nitrogen oxide (NO$_X$) and carbon dioxide (CO$_2$) emissions [3]. In general, an engine running on LNG according to the Otto cycle has about a 25% lower level of CO$_2$ emissions and about an 85% lower level of NO$_X$ emissions when compared to a conventional diesel-fueled engine [4]. This enables compliance with the IMO Tier III level and SO$_X$ regulations in designated emission control areas (ECAs).

Because of the growth in numbers of LNG-fueled ships, the high LNG bunkering demand has been issued subsequently. Thus, more efficient delivery methods with larger capacity and higher rates

are needed. The most favorable option for LNG bunkering is to transfer the LNG fuel by bunkering vessels (ship-to-ship, or StS) because of their larger delivery capacity and higher bunkering rates than conventional truck-to-ship (TtS) bunkering methods [5].

For the LNG bunkering vessel (LNGBV), its major problem is to deal with the boil-off gas (BOG) due to economic and environmental reasons. The BOG is the quantity of liquid that changes to the gas phase, and the boil-off rate (BOR) is dependent on the tank surface area, its heat conductivity, fuel thermodynamic state, and the temperature outside of the tank [6]. Common values of the BOR are around 0.1% to 0.15%/day for large LNG carriers as the maximum value; however, small LNG carriers have a large surface-to-volume ratio, resulting in a high BOR of 0.2% to 0.6%/day [7], and it is changeable depending on the tank type (particularly, its insulation materials) and amount of heat ingress.

Especially, during LNG (un)loading modes, a far greater amount of BOG is generated than in normal operation modes. In the case of the loading mode (from an LNG terminal tank to an LNGBV tank), the filling with new LNG could generate dominant BOG because of insufficient cold conditions inside the receiving tank and high heat ingress [8]. Similarly, this situation could happen during bunkering modes that transfer LNG from an LNGBV to an LNG receiving vessel. In order to handle this excessive BOG, the LNGBV should digest it in an appropriate way [9].

It is not difficult to handle the excessive BOG in the normal full-loading voyage condition, because the BOG can be used as fuel to the main engine or genset(s) (a generator engine combined with an alternator), which have high power demands for propulsion. However, when the ship is in port or slow steaming, the main engine or genset(s) have just low power demands, so the excessive BOG has to be handled by other methods [10]. Therefore, some ship owners take into account whether to install the re-liquefaction unit or not, because these sharp fluctuations in BOG during (un)loading could bring economic losses [11].

In general, the BOG re-liquefying system requires a large space and initial investment. In addition, it requires additional electric power demands. In general, the power consumption of the BOG re-liquefaction unit is about 0.7–0.8 kWh/kg [12,13]. Therefore, some methods have been continuously studied for LNG carriers; the partial re-liquefaction system [14], the high-efficient small-scaled re-liquefaction system [15], etc. Nevertheless, it might be impractical for the LNGBV, because the design capacity of the re-liquefaction system for the short BOG peak period would be unnecessarily large [16]. In other words, its size and the initial investment are relatively high to the small-sized LNGBV compared to the large-sized LNG carriers. Thus, the adoption of the re-liquefaction system to the LNGBV is not too many, as shown in Table 1.

Table 1. The list of liquefied natural gas (LNG) bunkering vessels (in operation).

Vessel Name	Capacity (m^3)	Delivery	Propulsion	BOG as Fuel	Re-Liquefaction	Reference
Seagas	180	2013 (retrofit)	Diesel engine	No	No	[17,18]
Engie Zeebrugge	5100	2017	Dual-fuel engine	Yes	No	[19]
Coralius	5800	2017	Dual-fuel engine	Yes	No	[19]
Cardissa	6500	2017	Electric motor	Yes	Yes (500 kg/h)	[19]
Oizmendi	600	2018 (retrofit)	Electric motor	Unknown	Unknown	[20]
Karios	7500	2018	Electric motor	Yes	No	[19]
Clean Jacksonville	2200	2018	Non-self-propelled barge	No	Yes (5.4 t/day)	[21,22]
Coral Methane	7500	2018 (retrofit)	Electric motor	Yes	Yes	[23,24]

In order to solve the BOG issue for LNGBVs, some studies have been performed to verify the causes of dominant BOG generation during bunkering operations. Shao et al. [25] investigated the amount of BOG generation, and revealed that the amount of BOG is proportional to the temperature difference between the bunkering tank and the receiving tank. In other words, if the temperature of the

receiving tank is higher, more BOG will return from inside the tank. Ryu [16] identified the primary causes of BOG generation and compared the BOG handling alternatives. In one handling alternative, Arias et al. [26] proposed hydrogen production through a steam-reforming plant using the excess BOG as raw material for a large LNG carrier. However, this area needs further studies to determine whether sufficient space is available, because an LNGBV has a much smaller space than an LNG carrier.

In this regard, this paper proposes another alternative to solve the BOG issue by using the energy storage system (ESS). The rest of this paper is structured as follows. In Section 2, detailed explanations of a target ship and the assumptions in this study are presented. In Section 3, two proposed systems are described based on the target ship. In Section 4, the amount of BOG generation and fuel consumption are calculated and compared with the conventional system. Additionally, an economic and environmental study based on the entire lifetime of a ship is performed in that section. Lastly, the results are reviewed, along with a conclusion. The novelty of this paper is a new approach to solve the BOG issue for LNGBVs by applying the ESS, and this could contribute to lessening environmental concerns in the marine industry.

2. Target Ship and Assumptions

The LNGBV for coastal trades might typically range from 1000 m^3 to 20,000 m^3 [27]. In this study, the target ship is set to have the storage capacity of 5000 m^3 for the receiving vessel, which is located within a short distance of about 27 nm (50 km). Its BOR is set to 0.3%/day for the laden voyage, and 0.08%/day for the ballast voyage considering several references [3,4,14–16]. The voyage concept for the target ship is shown in Figure 1.
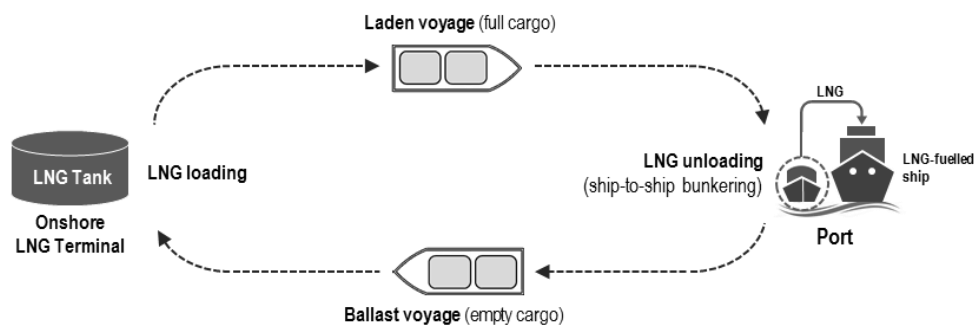

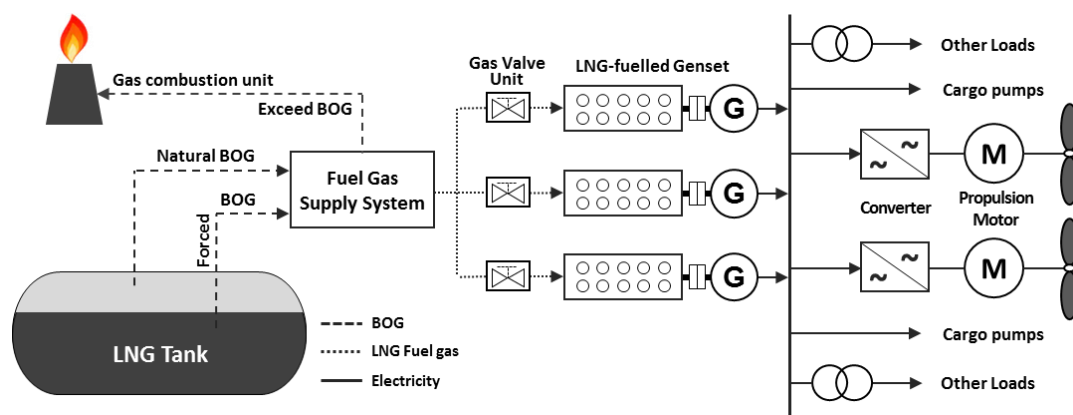**Figure 1.** Concept of an LNG ship-to-ship bunkering.

Figure 2. The concept diagram of the conventional system (S1).

Table 2. The assumed specifications of the target ship. BOR: boil-off rate.

Category	Specification
Voyage distance	Abt. 27 nm (50 km)
Speed	Abt. 13 knot (85% NOR)
Cargo capacity	5000 m^3
Cargo tank type	IMO Type C (independent tank)
Propulsion type	Electric propulsion
Generator	1.5 MW × 3 sets (LNG-fuelled)
BOR (minimum)	0.08% (ballast voyage)
BOR (maximum)	0.3% (laden voyage)
LNG density	446 kg/m^3 [28]

In this study, the assumed LNG density is 446 kg/m^3. This density can be different depending on its composition. In addition, the LNG composition is very crucial for meeting the required methane number to reduce knocking and misfiring risks in an LNG-fueled engine.

Besides, in this vessel, there are three gensets with 1.5-MW power each to supply electric power for propulsion as well as ship service loads; one or two gensets are sufficient to supply the load demands for all the operation modes, and the last genset is just for redundancy in accordance with the rule requirements [29]. These are all LNG-fueled gensets, so the BOG can be utilized for their fuel. Furthermore, the target ship is applied to the electric propulsion system due to its high station-keeping capability during bunkering operations. Its concept diagram is shown in Figure 2, and the assumed specifications of the target ship are shown in Table 2.

In addition, it is assumed that the target ship has no re-liquefaction unit for BOG handling; however, it reserves the weight and space margin for the future possible installation of the equipment. In general, the similar size of an LNGBV has the capacity of 500 kg/h for a re-liquefaction unit (Table 1). Therefore, it is assumed that the ship has 17 tons as a weight margin and 48 m^3 as a volume margin as per the average value of the manufacturers' specifications [30,31].

3. Case Study
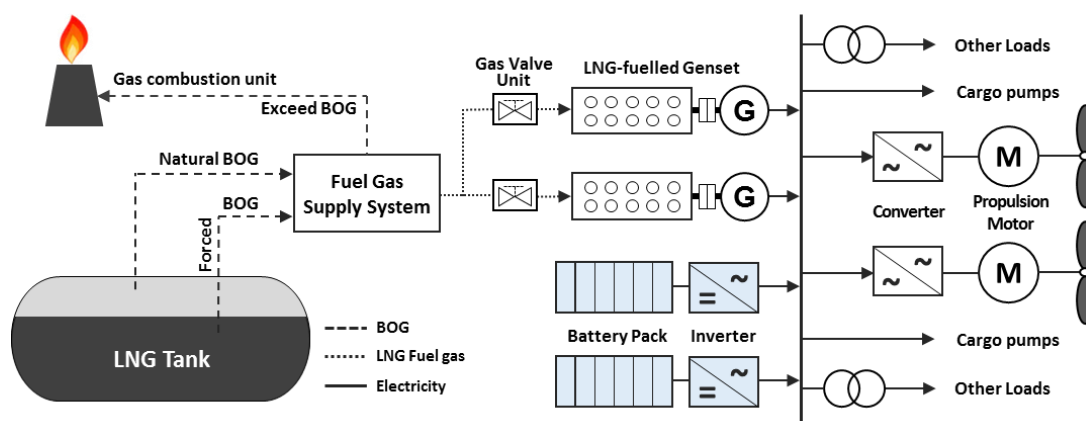
3.1. Proposed System

In order to reduce a considerable amount of BOG for the LNGBV, two ESS–hybrid power systems are suggested compared to the conventional system (S1). For the first proposed system (S2), the ESS is installed additionally with the limited capacity that is determined by the volume and weight marine discussed in Section 2. Secondly, the other system (S3) installs a greater capacity of ESS by eliminating one of gensets onboard. In this case, the additional capacity of the ESS is limited to the volume and weight of the one genset being replaced; these limit values are based on several manufacturers' specifications, as shown in Table 3. The concepts of the proposed systems are described in Figure 3a,b.

Table 3. The list of volume and weight of LNG-fueled gensets.

Manufacturer	Rating Power (kW)	Volume (m^3)	Weight (ton)	Model (60Hz)	Reference
Hyundai Heavy Industries	1516	46.4	37.3	H27DF	[32]
Wärtsilä	1600	44.0	23.9	9L20DF	[33]
MAN & Diesel	1520	46.2	40.7	8L28/32DF	[34]
Rolls-Royce	1401	51.1	33.9	C26:33L6AG	[35]
Average	Abt. 1500	46.9	34.0	-	-
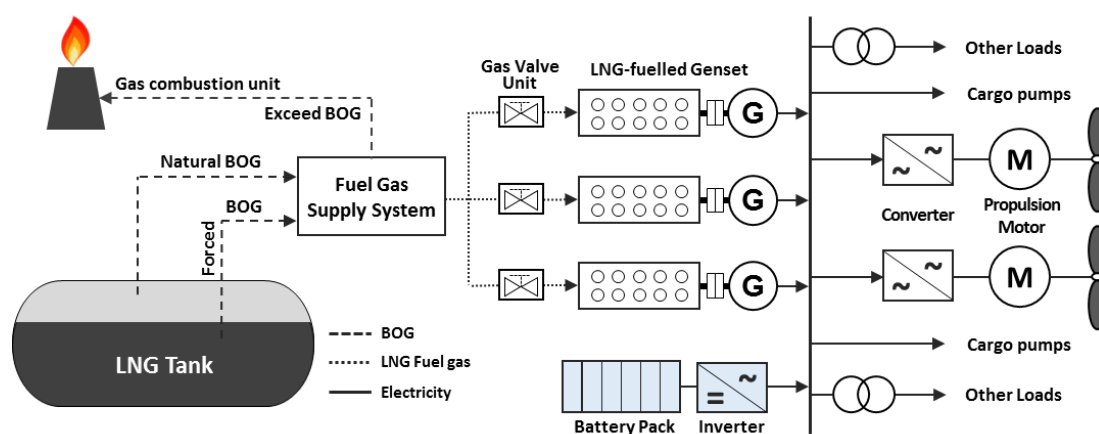
(**a**) Proposed system (S2).

(**b**) Proposed system (S3).

Figure 3. The concept diagram of the proposed systems. (**a**) the proposed system of S2, which has the ESS compared with the S1, and (**b**) the proposed system of S3, which has additional ESS compared with the S2 by eliminating one genset.

3.2. ESS Capacity

The specifications of the ESS in this study are shown in Table 4. In order to determine the ESS capacity under the volume and weight limits, the below equations are used, which are the results from a study [36]; these developed the trends of volume and weight based on manufacturers' specifications.

Table 4. The assumed specifications of the energy storage system (ESS) in this study. DoD: depth of discharge, SoC: state of charge.

Category	Specification
Cell type	Lithium ion
Nominal voltage	750 V
DoD (SoC range)	80% (10–90%)
C-rate	1.0
Efficiency	95% (Battery: 97%, Inverter: 98%)
Lifetime	10 years

$$\text{Energy [kWh]} = 0.075 \times \text{Weight [kg]} - 2.8172 \tag{1}$$

$$\text{Energy [kWh]} = 72.268 \times \text{Volume} \left[\text{m}^3 \right] - 5.0624 \tag{2}$$

Therefore, the maximum available ESS capacity is determined to 1250 kWh for S2, which is under the margin discussed in Section 2. For S3, the ESS capacity is determined as 3800 kWh considering the additional weight and volume margin by eliminating one genset (Table 3). Even though the ESS is installed with the determined capacity, it cannot discharge or charge its energy fully, but its maximum useful energy ($E_{usuable}$) is reduced as below:

$$E_{usuable} = (E_{installed} \times k_{dod})/k \tag{3}$$

where $E_{installed}$ is the installed energy, k_{dod} is the depth of discharge (DoD), and k is the safety margin considering temperature and aging factors, etc. In this study, k_{dod} is assumed to be 80%, and k is assumed to be 1.2. Then, the maximum usable energy of the ESS for S2 is about 833 kWh, and about 2533 kWh for S3.

4. Results and Discussion

4.1. BOG and Fuel Comparison

The total mass of the BOG generated is depending on the volume of the LNG cargo capacity (V [m^3]), LNG density (ρ [kg/m^3]), BOR [%/day], time spent (t [hour]), and calculated as below:

$$\text{BOG}_{generated}[\text{kg}] = \frac{V \times \rho \times \text{BOR}}{24} \times t \tag{4}$$

Furthermore, the fuel consumption of gensets is dependent on the required energy (E [kWh]) and specific fuel gas consumption (SFGC) [g/kWh], and the efficiency (η_{FGSS}) of the fuel gas supply system (FGSS). The FGSS is used to vaporize LNG and supply natural gas to gensets under the specified temperature and pressure conditions, and it consists of compressors, vaporizer, pumps, etc. Therefore, the amount of LNG fuel consumption of genset(s) is calculated as below:

$$\text{Fuel}_{consumed}[\text{kg}] = \frac{E \times \text{SFGC(i)}}{\eta_{FGSS}} \times 10^{-3} \tag{5}$$

where η_{FGSS} is assumed to be about 60% in this study, and a small amount of pilot diesel fuel (less than 1% [37,38]) is not considered in this study for the simplification. The different SFGC values are applied according to the range of load factors (i), as shown in Table 5.

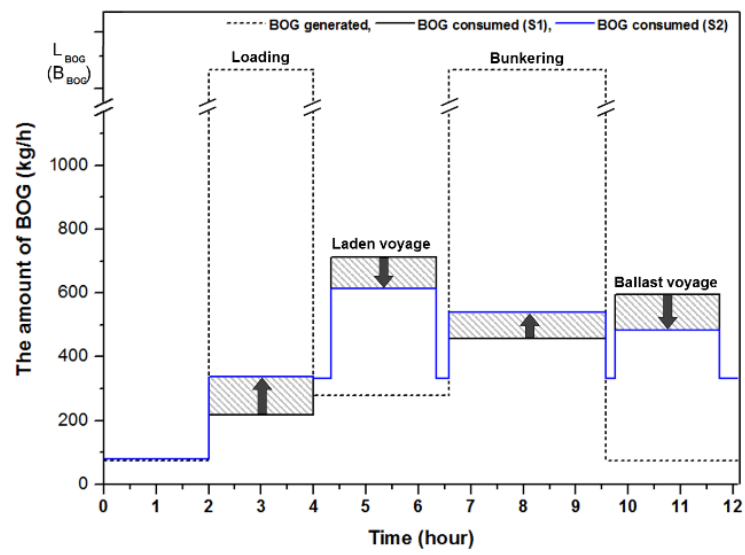**Table 5.** The assumed specific fuel gas consumption (SFGC) for the LNG genset according to the load factor.

Load Factor (L.F)	SFGC (kJ/kWh) [33]	SFGC (g/kWh)
L.F. < 50%	8189	165.03
50% ≤ L.F. < 75%	8314	167.55
75% ≤ L.F. < 85%	8493	171.16
85% ≤ L.F. < 100%	9211	185.63

The amount of BOG generated is dominant during LNG loading at an LNG terminal and bunkering at a bunkering port. This amount is very fluctuating depending on the situations; therefore, it is denoted as L_{BOG} for the BOG during loading operations, and B_{BOG} during bunkering operations in this study. For the laden voyage, the BOG generated is not enough, and some additional LNG fuel is required. After LNG bunkering, the BOG generated is reduced because of the empty fuel tanks,
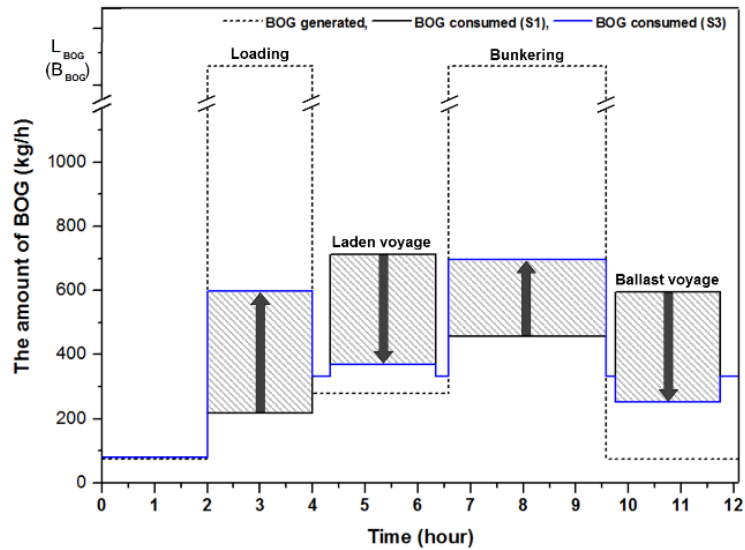
so more LNG fuel is required to operate the gensets. The amount of BOG generated and the BOG consumed for each operation mode is shown in Table 6.

Table 6. The BOG generated and consumed for each operation mode (BOR: minimum 0.08%/d, maximum 0.3%/d, L_{BOG} and B_{BOG}: 1000 kg/h). BOG: boil-off gas.

Operating Mode		Unit	Harbor	During Loading	Maneuvering (Port out)	Laden Voyage	Maneuvering (Approaching)	During Bunkering	Maneuvering (Leaving)	Ballast Voyage	Maneuvering (Port in)
Required power		kW	255	765	1190	2550	1190	1605	1190	2091	1190
Operating time		-		2 h	2 h	20 min	2 h	15 min	3 h	10 min	2 h	20 min
BOG generated		kg	148.67	2000 (L_{BOG})	92.92	557.50	69.69	3000 (B_{BOG})	12.39	148.67	24.78
S1	Genset (s) No.		1	1	1	2	1	2	1	2	1
	Genset (s) kW		255	765	1190	2550	1190	1605	1190	2091	1190
	Load factor (%)		17.0	51.0	79.3	85.0	79.3	53.5	79.3	69.7	79.3
	BOG consumed by genset (s)	kg	157.79	436.46	110.77	1424.20	83.08	1373.57	55.39	1192.99	110.77
S2	Genset (s) No.		1	1	1	2	1	2	1	2	1
	Genset (s) kW		255	1203	1190	2154	1190	1896	1190	1695	1190
	Load factor (%)		17.0	80.2	79.3	71.8	79.3	63.2	79.3	56.5	79.3
	ESS kW		-	–416	-	416	-	–276	-	416	-
	ESS kWh		-	–832	-	832	-	–829	-	832	-
	BOG consumed by genset (s)	kg	157.79	671.89	110.77	1228.93	83.08	1622.60	55.39	967.06	110.77
S3	Genset (s) No.		1	2	1	1	1	2	1	1	1
	Genset (s) kW		255	2097	1190	1344	1190	2493	1190	885	1190
	Load factor (%)		17.0	69.9	79.3	89.6	79.3	83.1	79.3	59.0	79.3
	ESS kW		-	–1265	-	1266	-	–844	-	1266	-
	ESS kWh		-	–2531	-	2533	–	-2531	–	2533	-
	BOG consumed by genset (s)	kg	157.79	1196.41	110.77	739.35	83.08	2,088.55	55.39	504.92	110.77

In the case of S3, which has two gensets, only one genset and the ESS can supply the required power during all the operation modes, except for the loading and bunkering modes. In other words, although one genset failed in the seagoing mode, the ship can return to the port safely by using the remaining standby genset.

The change of the BOG generated and consumed for the conventional system (S1) and proposed one (S2) are compared in Figure 4a, and between S1 and S3 are compared in Figure 4b. For the S2 and S3 cases, when the amount of BOG is too much, the BOG is consumed additionally by using it for the ESS charging. Therefore, the reduced amount of BOG can be about 117.7 kg/h for L_{BOG}, 83.0 kg/h for B_{BOG} in the case of S2, and 380.0 kg/h for L_{BOG}, 238.3 kg/h for B_{BOG} in the case of S3. If the L_{BOG} and B_{BOG} are assumed to be about 1000 kg/h each, the reduction rate compared with S1 is 15.2% for S2, and 46.2% for S3. In addition, when the amount of BOG is too small, the proposed systems require less LNG fuel by using the stored energy in the ESS. In other words, the fuel shortage of the gensets can be compensated by the ESS. Assuming that the BOR is a minimum of 0.08%/day and a maximum of 0.3%/day, the fuel consumption decreases to 20.2% for the S2 system, and 66.0% for the S3 system compared with the conventional system (S1). In addition, in the case of the higher BOR condition, the fuel reduction rate increases because of the increased amount of BOG (Figure 5).

(**a**) S1 vs. S2.

(**b**) S1 vs. S3.

Figure 4. The comparison of the BOG generation and consumption. (**a**) comparison between S1 and S2, and (**b**) comparison between S1 and S3, which shows higher BOG consumption and lower BOG shortage.
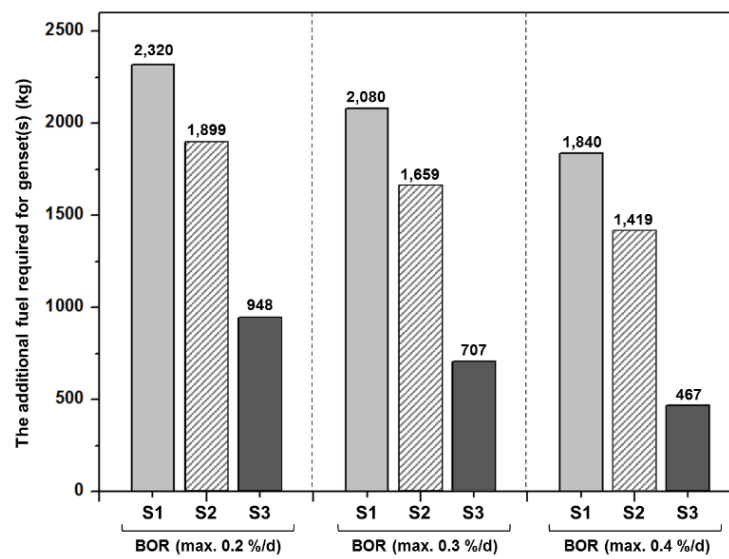
Figure 5. The amount of fuel required additionally during the BOG shortage conditions.

The changes of the power output and state of charge (SoC) of the ESS during one voyage are shown in Figure 6. The SoC is calculated using the MATLAB/Simulink software (MathWorks, Natick, MA, USA) based on the defined specification in Table 4. Figure 6a,b show that the SoC of each ESS is within the allowable operation range of 10% to 90%.

(a) S2.　　　　　　　　　　　　　　　　　　**(b)** S3.
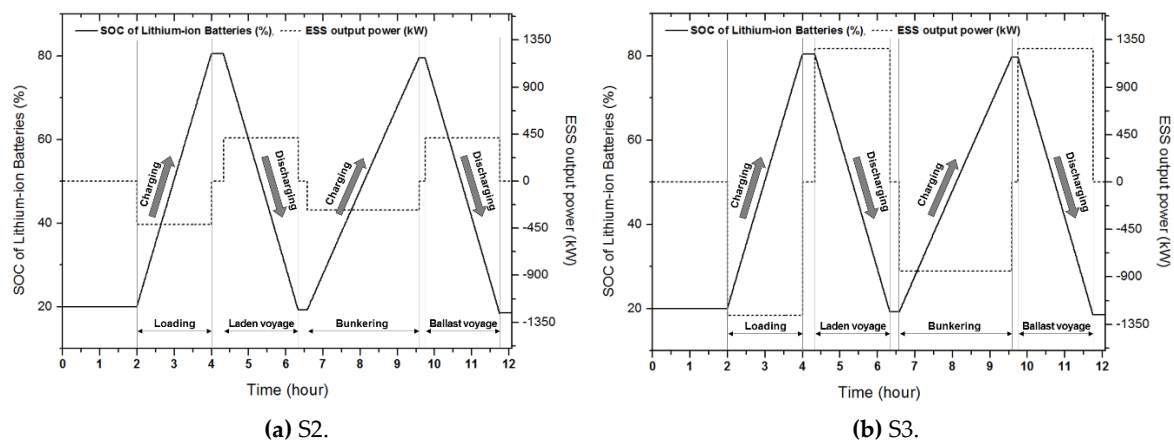
Figure 6. The change of the output power and SoC of the energy storage system (ESS) for the proposed systems. (**a**) the proposed system of S2, and (**b**) the proposed system of S3, in which the dotted line indicating output power (kW) and the solid line indicating SoC (%) of each ESS.

4.2. Lifetime Cost Comparison

An economic study was carried out to compare the conventional power system and proposed ones based on the assumptions in Table 7. In this study, only the main equipment was considered, so the initial capital expenditure (CAPEX) is the sum of the main equipment cost for each system. For the operational expenditure (OPEX), the fixed operations and maintenance (O&M) cost and gensets' fuel cost are considered. The variable O&M costs, which include the cooling water or consumable materials used in maintenance, are assumed to be negligible, because they comprise a relatively small portion in general power systems [39–41].

Table 7. Assumptions for the economic study. PCS: Power conditioning system, FGSS: fuel gas supply system, O&M: operations and maintenance.

Item		Assumption	Reference
Equipment cost	LNG genset	$500/kW	[42]
	Li-ion batteries	$400–600/kWh	-
	Converter (PCS)	$200/kW	[43]
	Gas combustion unit	$500/kg/h	[44]
	FGSS	$500,000 [1]	[45]
Fixed O&M cost	LNG genset	$15/kW/yr	[46]
	Li-ion batteries	$0.5/kW/yr	[47]
	Converter (PCS)	$2/kW/yr	[48]
	Gas combustion unit	2.5% of CAPEX	[49]
	FGSS	2.5% of CAPEX	[49]
LNG fuel cost		$350–550 /ton	[50–52]
Interest rate (i)		5%	-
Fixed O&M cost inflation rate (e_1)		2%	-
Fuel increasing rate (e_2)		3%	[53]

[1] The cost is adjusted considering the difference in capacity from the reference value.

The cost of lithium-ion batteries (LIBs) is the assumed value obtained from manufacturers, and it is mostly higher than mass-produced land-based applications such as cars, power plants, etc. In general, the energy-type LIB is used to supply energy with a low C-rate for a long time, and the power-type LIB is used to supply energy with a high C-rate for the peak time. In this case, the ESS is set to operate with an 1.0 C-rate; thus, the energy-type LIB is selected, which is cheaper than the power-type. This LIB has to be replaced with new one after its lifespan of about 10 years, and the LIB cost is assumed to be cut down by 50% after a decade based on references [54,55].

In the case of the gas combustion unit (GCU), proposed systems can reduce its capacity because of the reduced BOG as discussed in Section 4.1. For S3, additionally, the capacity of the FGSS can be reduced by eliminating one of gensets; this cost saving is assumed to be $100,000 considering manufacturers' opinions.

Therefore, the cumulative saving cost of the proposed system is calculated as below. The initial investment is the additional cost of the proposed system (I_{S2}, I_{S3}) compared to the conventional system (I_{S1}). The replacement cost for the batteries (R_B) after each 10-year period is also considered as below. Furthermore, the total savings during N years (S_{total}) is the sum of the yearly savings (S_n), taking into account the interest rate (i) for the capital [56].

$$\text{Cumulative saving cost} = (I_{s2(s3)} - I_{s1}) - S_{total} - R_B|_{n=10} - R_B|_{n=20} \tag{6}$$

$$S_{total} = \sum_{n=1}^{N} \frac{S_n}{(1+i)^n} = S_{Fixed\ O\&M} + S_{Fuel} \tag{7}$$

The savings from the reduced fixed O&M cost ($S_{Fixed\ O\&M}$) and the reduced fuel cost (S_{Fuel}) for N years are calculated each as below.

$$S_{Fixed\ O\&M} = \sum_{n=1}^{N} \frac{(1+e_1)^n \left(F_{s1} - F_{s2(s3)}\right)}{(1+i)^n} \tag{8}$$

$$S_{Fuel} = \sum_{n=1}^{N} \frac{(1+e_2)^n \left(G_{s1} - G_{s2(s3)}\right)}{(1+i)^n} \tag{9}$$

where $F_{S1,2,3}$ is the fixed O&M cost, and $G_{S1,2,3}$ is the LNG fuel cost for each system (S1, S2, and S3). Thus, the payback period is calculated by solving for n when the initial investment cost is equal to the

sum of the yearly savings. The payback occurs where the curve passes through the zero of the y-axis in the case of the original values. For S2, the payback occurs at around 24.6 years, and for S3, it occurs at around 7.6 years firstly, and then it comes again at around 12.4 years due to the LIB replacement, assuming that the LNG fuel cost is $450/ton, the bunkering time is once a day, and the LIB cost is $500/kWh. In addition, the internal rate of return (IRR) is 5.1% for S2 and 9.1% for S3, which are higher than the assumed interest rate (5%). Therefore, both systems could be acceptable.

In accordance with critical variables, the payback period is changeable, as shown in Figure 7 for S2 and Figure 8 for S3. The proposed system of S2 seems to be uneconomical compared with the conventional one due to its long payback period and low IRR. However, S3 seems to be economical, particularly for some conditions: high LNG fuel cost, high bunkering times, and low LIB cost, etc.
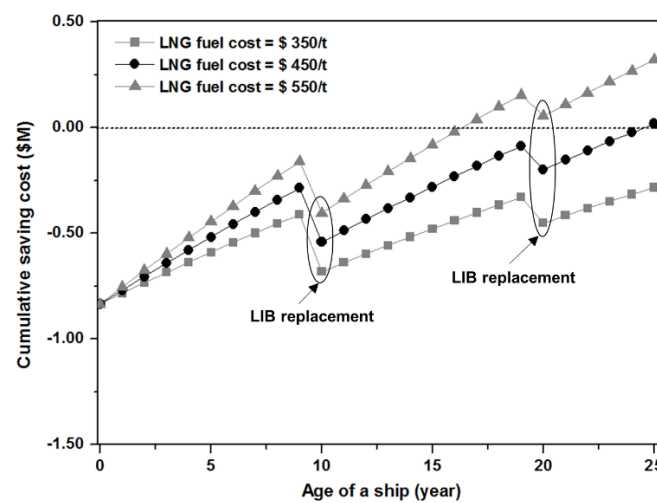
(**a**) LNG fuel cost variations (assumptions: bunkering = 1 time/day, LIB cost = $500/kWh). LIB: lithium-ion batteries.
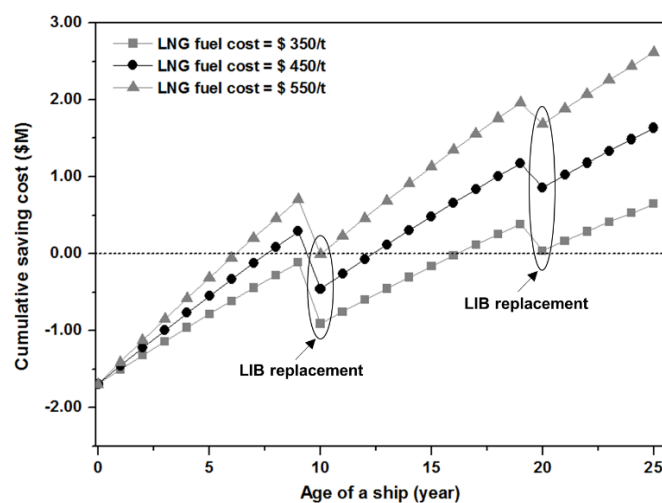
Figure 7. *Cont.*
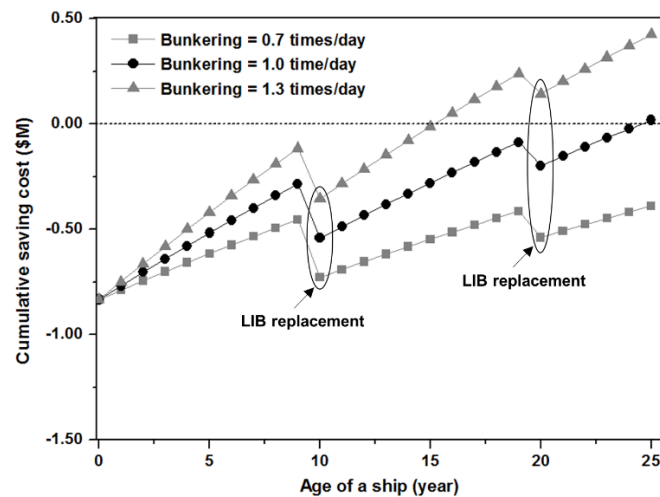
(**b**) Bunkering time variations (assumptions: LNG fuel cost = $450/t, LIB cost = $500/kWh).
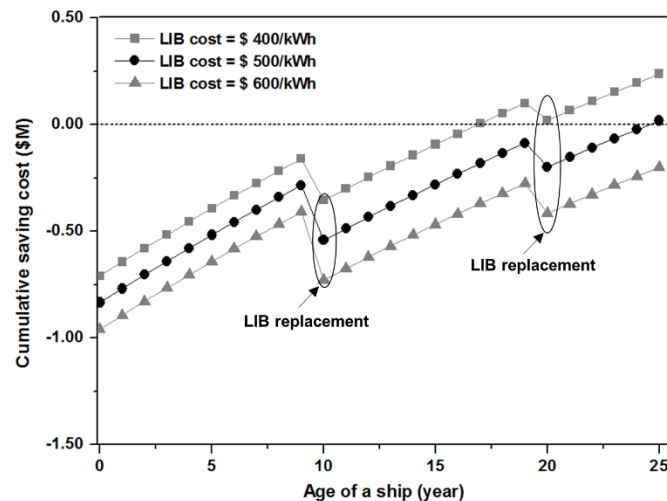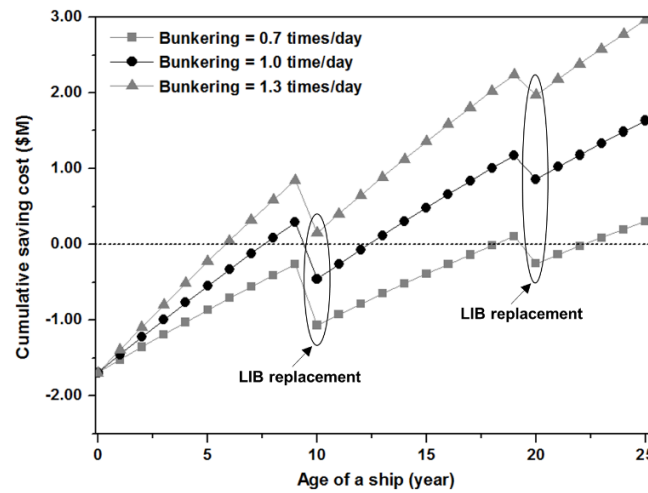

(**c**) LIB cost variations (assumptions: LNG fuel cost = $450/t, bunkering = 1 time/day).

Figure 7. Cumulative saving cost depending on different variations for S2. (**a**) cumulative saving cost with different LNG fuel cost, (**b**) cumulative saving cost with different bunkering times, and (**c**) cumulative saving cost with different LIB cost.
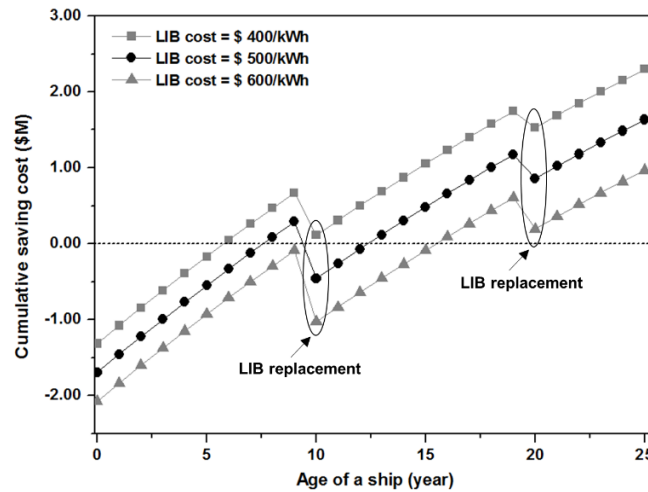

(**a**) LNG fuel cost variations (assumptions: bunkering = 1 time/day, LIB cost = $500/kWh).

Figure 8. *Cont.*

(**b**) Bunkering time variations (assumptions: LNG fuel cost = $ 450/t, LIB cost = $500/kWh).

(**c**) LIB cost variations (assumptions: LNG fuel cost = $450/t, bunkering = 1 time/day).

Figure 8. Cumulative saving cost depending on different variations for S3. (**a**) cumulative saving cost with different LNG fuel cost, (**b**) cumulative saving cost with different bunkering times, and (**c**) cumulative saving cost with different LIB cost.

4.3. GHG Emission Comparision

The SO_X, NO_X, and PM emissions from the LNG-fueled combustion operations are far less than those of the HFO fuel, as discussed in Section 1. Therefore, in this study, only GHG emissions are considered, which mainly consist of three emission types: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). GHG emissions are calculated using the CO_2-equivalent global warming potential by directly summing the 100-year conversion coefficients recommended by the 5th Assessment Report (AR5) of the Intergovernmental Panel for Climate Change (IPCC) for the three main GHG emission types as below [57]:

$$E(GHG) = E(CO_2) + 28 \times E(CH_4) + 265 \times E(N_2O) \tag{10}$$

As shown in Equation (10), the CH_4 that is the main constituent of LNG has significantly strong impacts on the total GHG emissions. In addition, if a 20-year conversion coefficient is applied, this gives larger impacts on the total GHG emissions due to a much higher CH_4 conversion coefficient of 84; it is three times higher than the 100-year conversion coefficient [57]. Therefore, the excess of the BOG is not allowed to release directly into the atmosphere for environmental concerns as well as safety reasons [58]. Nevertheless, in an emergency situation, venting the BOG by activating the emergency release system (ERS) could be allowed to prevent hazardous situations. The amount of emissions

generated by each system ($E_{LNG}(i)$) according to its fuel consumption ($C(i)$) can be calculated as below using each emission factor (E_f), as shown in Table 8.

$$E_{LNG}(i) = \{E_f(CO_2) \times C(i)\} + \{28 \times E_f(CH_4) \times C(i)\} + \{265 \times E_f(N_2O) \times C(i)\} \qquad (11)$$

Table 8. Greenhouse gas (GHG) emission factors for LNG fuel.

Emission Type	Emission Factor of LNG
CO_2 [g CO_2/g LNG]	2.75 [59]
CH_4 [g CH_4/g LNG]	0.025 [60,61]
N_2O [g N_2O/g LNG]	6.33×10^{-5} [59]

In this study, GHG emissions are categorized into two parts. Firstly, emissions from the GCU (E_{GCU}) are generated through the GCU for the LNG loading or bunkering mode, in that a huge amount of BOG is generated. Secondly, the emission from the genset(s) (E_{GEN}) is emitted by its combustion operations, and which is proportional to its amount of fuel consumption. The amount of GHG emissions from each system is shown in Figure 9 based on Table 6.
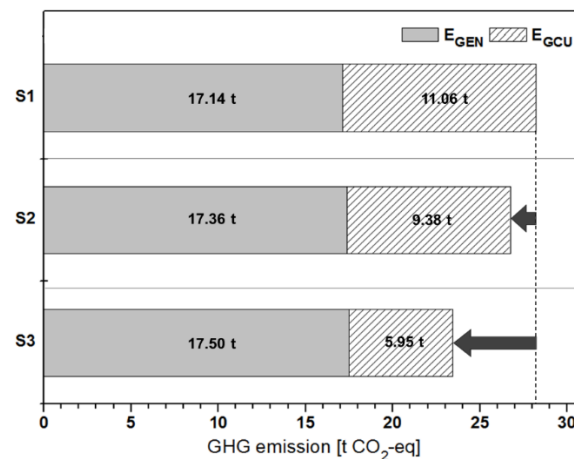

Figure 9. The comparison of GHG emissions for one voyage (assumptions: L_{BOG} and B_{BOG} = 1000 kg/h).

Even though the E_{GEN} for the proposed systems is a little bit higher than that for a conventional system (1.3% for S2, and 2.1% for S3) due to the ESS charging, S2 and S3 have less GHG emissions in total due to the reduced E_{GCU}. Therefore, the amount of GHG reduction per voyage can reach 1.46 tons (5.2%) for S2 and 4.75 tons (16.8%) for S3. If an LNGBV operates one voyage per day, the amount of GHG emitted during a year can be reduced up to about 533 tons for the S2, and about 1734 tons for S3. To put these figures in perspective, they are equivalent to the emissions from 122 gasoline-fueled cars for S2 and 396 cars for S3, assuming that a car travels 11,500 miles per year with 381 g CO_2-eq per mile [62,63].

5. Conclusions

This paper presents a new alternative to solve the excessive BOG issue for LNG bunkering vessels. Two types of hybrid systems combining conventional genset(s) with ESS are proposed; the first system (S2) has 1250-kWh capacity and the second system (S3) has a capacity of 3800 kWh. For each system, the amount of the BOG generated and its fuel consumption are calculated and compared with the conventional one (S1). Then, the economic and environmental benefits are compared for each system. The results of this study are summarized as follows.

- Using the ESS with genset(s) can have eco-economic benefits: BOG reduction (from 15% to 46%), fuel reduction (from 20% to 66%), and GHG reduction (from 5% to 17%). When comparing S2 and S3, S3 appears to be more economical and environmentally-friendly.
- Even though S2 seems to be uneconomical due to its long payback period (24.6 years), it can contribute to reducing GHG emissions (1.46 t/voyage).
- The payback period can be shorter for some conditions: high LNG fuel cost, high bunkering times, and low LIB cost.

Through this study, it was confirmed that the problem of BOG fluctuations of LNGBVs can be solved using the ESS. However, the following topics require further future study:

- A comprehensive comparison between the re-liquefaction facility and the proposed ESS–hybrid system as a solution for the BOG issue, focusing on the economic feasibility, the environmental-friendliness, required space and weight, etc.
- An additional consideration would be required for a longer distance voyage; S3, which has only two gensets, is only possible for short distances due to the power redundancy requirements.

An additional consideration would be required for the LNG density, which is different depending on its actual composition.

In the case of the re-liquefaction facility, the fuel savings by re-liquefying the BOG is a main advantage, while the additional fuel consumption due to the increased electric power is a disadvantage. In addition, the re-liquefaction efficiency, which is dependent on the type of re-liquefaction process, should be considered in the economic analysis.

The number of LNG-fueled vessels has been increasing rapidly, and there are 143 LNG-fueled vessels in operation worldwide as of January 2019 [64]. In addition, the LNG bunkering infrastructure is being developed at major ports including Zeebrugge port, Rotterdam port, and Singapore port. These LNG bunkering ports are mostly serviced with small-scale LNG bunker ships such as this target ship [65]; thus, the number of LNGBVs is also expected to boost in the near future. Therefore, this proposed ESS-hybrid power system would contribute to increasing the LNGBV market by solving the BOG issues as well as environmental concerns in the marine industry.

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References

1. Walker, T.R.; Adebambo, O.; Del Aguila Feijoo, M.C.; Elhaimer, E.; Hossain, T.; Edwards, S.J.; Morrison, C.E.; Romo, J.; Sharma, N.; Taylor, S.; et al. Environmental effects of marine transportation. In *World Seas: An Environmental Evaluation*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 505–530.
2. IMO. Low Carbon Shipping and Air Pollution Control. Available online: http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/default.aspx (accessed on 11 March 2019).
3. Sastre Buades, L. Implementation of LNG as Marine Fuel in Current Vessels. Perspectives and Improvements on Their Environmental Efficiency. Master's Thesis, Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, 2017.
4. Kackur, J. *Shipping in the 2020 Era—Selection of Fuel and Propulsion Machinery—Business White Paper*; Wärtsilä: Helsinki, Finland, 2018.
5. International Maritime Organization (IMO). *Studies on the Feasibility and Use of LNG as a Fuel for Shipping*; International Maritime Organization (IMO): London, UK, 2016; p. 48.
6. Klein, R. *Cruise Ship Concepts Applying LNG Fuel*; TTÜ Masinaehituse Instituut: Tallinn, Estonia, 2016.

7. Harperscheidt, J. *LNG Bunkering—LNG as a Ship's Fuel*; TGE: Shanghai, China, 2011.

8. EMSA (European Maritime Safety Agency). *Guidance on LNG Bunkering to Port. Authorities and Administrations*; EMSA (European Maritime Safety Agency): Lisbon, Portugal, 2018; p. 77.

9. Jang, D. Note on critical issues with boil-off gas generating from marine fuel LNG. *Ocean. Fish. Open Access J.* **2017**, *1*. [CrossRef]

10. Natural Gas Gloval (NGV). Space-Fitting Prismatic Pressure Vessel for Fuel LNG Storage. Available online: http://naturalgasglobal.com/2017/02/03/619/ (accessed on 3 February 2017).

11. Yajun, L.; Yue, L. Dynamic optimization of the boil-off gas (BOG) fluctuations at an LNG receiving terminal. *J. Nat. Gas Sci. Eng.* **2016**, *30*, 322–330. [CrossRef]

12. Arrigo, B. Boil-off Gas Handling on LNG Fuelled Vessels with High Pressure Gas Injected Engines. Master's Thesis, Politecnico Di Milano & NTNU (Norwegian University of Science and Technology), Trondheim, Norway, 2015; p. 18.

13. Leidos Corporation. *Marine Fuel Choice for Ocean-Going Vessels within Emissions Control Areas*; U.S. Energy Information Administration (EIA): Washington, DC, USA, 2015; p. 27.

14. Yun, S.-K. Characteristics of boil-off-gas partial re-liquefaction systems in LNG ships. *J. Korean Soc. Mar. Eng.* **2016**, *40*, 174–179. [CrossRef]

15. Kwak, D.-H.; Heo, J.-H.; Park, S.-H.; Seo, S.-J.; Kim, J.-K. Energy-efficient design and optimization of boil-off gas (BOG) re-liquefaction process for liquefied natural gas (LNG)-fuelled ship. *Energy* **2018**, *148*. [CrossRef]

16. Ryu, J. Concept for Protection Against Overpressure Caused by BOG Generated During Ship-to-Ship LNG Bunkering. Master's Thesis, KAIST, Daejeon, Korea, 2012.

17. Sirius Shipping. LNGF Seagas. Available online: http://www.siriusshipping.eu/ship/lngf-seagas/ (accessed on 3 March 2019).

18. Hatley, J. Seagas LNG bunkering viking grace. Presented at the LNG Bunkering Roundtable in conjunction with 19th Singapore International Bunkering Conference and Exhibition (SIBCON), Sentosa, Singapore, 5 October 2016.

19. Choi, W.J.; Navarro, J.M.; Tustin, R.D. Purpose designed LNG bunkering vessels (1). *SWZ Marit. Marit. Tech. Vakbl.* **2018**, *139*, 36–40.

20. Veristar. Register -Sea-going Ships. Available online: https://www.veristar.com/portal/veristarinfo/generalinfo/registers/seaGoingShips (accessed on 7 March 2019).

21. Stirling Cryogenics. LNG Bunker Barge Jacksonville USA. Available online: https://www.stirlingcryogenics.eu/en/projects/maritime/lng-bunker-barge-jacksonville-usa (accessed on 13 March 2019).

22. Marex. North America? First LNG Bunker Barge Delivered. The Maritime Executive. Available online: https://maritime-executive.com/article/north-america-s-first-lng-bunker-barge-delivered (accessed on 20 August 2018).

23. Coral Methane Multipurpose LNG Carrier. Ship Technology. Available online: https://www.ship-technology.com/projects/coralmethane/ (accessed on 9 March 2019).

24. Corkhill, M. LNG Bunker vessel fleet increases to 18 mark. *LNG World Shipp. Sept. Oct.* **2018**, *40*, 17–18.

25. Shao, Y.; Lee, Y.-H.; Kim, Y.-T.; Kang, H.-K. Parametric investigation of BOG generation for ship-to-ship LNG bunkering. *J. Korean Soc. Mar. Environ. Saf.* **2018**, *24*, 352–359. [CrossRef]

26. Arias Fernández, I.; Gómez, M.R.; Gómez, J.R.; López-González, L.M. H_2 Production by the steam reforming of excess boil off gas on LNG vessels. *Energy Convers. Manag.* **2017**, *134*, 301–313. [CrossRef]

27. Enerdata. LNG Bunkering Market Overview (posted at 19 December 2016). Available online: https://www.enerdata.net/publications/executive-briefing/development-lng-bunkering-executive-brief.html (accessed on 27 February 2019).

28. Dobrota, Đ.; Lalić, B.; Komar, I. Problem of—off in LNG Supply Chain. *Trans. Marit. Sci.* **2013**, *2*, 91–100. [CrossRef]

29. Korean Register (KR). *Classification rule—Part 6, Electrical Equipment and Control Systems*; Korean Register (KR): Busan, Korea, 2019.

30. Dioguardi, F.; Vermeulen, H. *Stirling Cryogenerators for Re-Liquefaction of Methane Boil-off Gas. on Ships*; Stirling Cryogenics: Eindhoven, The Netherlands, 2016.

31. Air Liquide. Turbo-Brayton for the Reliquefaction of BOG. Available online: http://advancedtech.airliquide.com/turbo-brayton-reliquefaction-bog (accessed on 11 February 2019).

32.	Hyundai HiMSEN. *Hyundai HiMSEN ENGINE—Programme 2018*, 2nd ed.; Hyundai HiMSEN: Ulsan, Korea, 2018.

33.	Wärtsilä. *Wärtsilä 20DF—Product Guide*; Wärtsilä: Helsinki, Finland, 2018.

34.	MAN Diesel & Turbo. *Marine GenSets from MAN Diesel & Turbo*; MAN Diesel & Turbo: Augsburg, Germany, 2014.

35.	Rolls-Royce. *Project Guide—Bergen Engine Type C26:33 Gas*; Rolls-Royce: Goodwood, UK, 2018.

36.	Minnehan, J.J.; Pratt, J.W. *Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels*; SAND-2017-12665, 1410178; Sandia National Laboratories: Albuquerque, NM, USA, 2017.

37.	Castel, J.-F.; Leriche, J. Feedback on the operation of the dual fuel diesel electric propulsion on LNG carriers: Impact of gas fuel quality on propulsion efficiency. In Proceedings of the 17th International Conference & Exhibition on Liquefied Natural Gas (LNG 17), Houston, TX, USA, 16–19 April 2013.

38.	MAN Diesel & Turbo. *Dual-Fuel Upgrade (Retrofit & Modernization for 4-Stroke Engines)*; MAN Diesel & Turbo: Augsburg, Germany, 2018.

39.	Sim, S. *Electric Utility Resource Planning: Economics, Reliability, and Decision-Making*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2011; ISBN 9781439884072.

40.	Sabol, S. *Case Studies in Mechanical Engineering: Decision Making, Thermodynamics, Fluid Mechanics and Heat Transfer*; John Wiley & Sons: Hobboken, NJ, USA, 2016; ISBN 9781119119746.

41.	Kelp, O.; Lenton, R.; Choudhuri, G. *Fuel and Technology Cost Review—Final Report*; Acil Allen Consulting: Sydney, Australia, 2014.

42.	Wartsila. *Business White Paper—LNG as a Marine Fuel Boosts Profitability While Ensuring Compliance*; Wartsila: Helsinki, Finland, 2017; p. 3.

43.	Aquino, T.; Roling, M.; Baker, C.; Rowland, L. *Battery Energy Storage Technology Assessment*; Platte River Power Authority: Fort Collins, CO, USA, 2017; p. 8.

44.	Norberg, A. Interrelationships of LNG Cargo Containment Systems and Machinery Configurations on LNG Carrier—Design and Operational Factors with Economic Assessment. Master's Thesis, NTNU (Norwegian University of Science and Technology), Trondheim, Norway, 2012.

45.	SEA/LNG STUDY—Newbuild 14,000 TEU Liner Vessel on Asia-USWC Trade. *LNG as a Marine Fuel—The Investment Opportunity*; SEA/LNG: Oxford, UK, 2019.

46.	Lazard. *Lazard's Levelized Cost of Energy Analysis—Version 8.0*; Lazard: New Orleans, LA, USA, 2014.

47.	Heinzmann, J. GE energy storage. In Proceedings of the Solar Power International 2016, Las Vegas, NV, USA, 12–15 September 2016.

48.	Viswanathan, V.; Kintner-Meyer, M.; Balducci, P.; Jin, C. *National Assessment of Energy Storage for Grid Balancing and Arbitrage Phase II*; Pacific Northwest National Laboratory: Richland, WA, USA, 2013.

49.	MRA (Malta Resources Authority). *Energy Interconnection Europe—Malta (Final Report–Work Package IIA)*; MRA (Malta Resources Authority), Lahmeyer International: Marsa, Malta, 2008; pp. 6–69.

50.	Ycharts. European Union Natural Gas Import Price. Available online: https://ycharts.com/indicators/europe_natural_gas_price (accessed on 9 March 2019).

51.	Growing LNG Marketplace to Drive Spot Shipping Rates in 2019 (posted on 8 January 2019). MFAME (Marine Fuels & Marine Engine Users). Available online: http://mfame.guru/growing-lng-marketplace-to-drive-spot-shipping-rates-in-2019/ (accessed on 3 March 2019).

52.	DNV GL. Current Price Development Oil and Gas. Available online: https://www.dnvgl.com/maritime/lng/current-price-development-oil-and-gas.html (accessed on 10 March 2019).

53.	COMESA. Natural Gas Prices Forecast: Long Term 2018 to 2030—Data and Charts. Available online: http://comstat.comesa.int/ncszerf/natural-gas-prices-forecast-long-term-2018-to-2030-data-and-charts (accessed on 1 March 2019).

54.	Curry, C. *Lithium-Ion Battery Costs and Market*; Bloomberg New Energy Finance: London, UK, 5 July 2017.

55.	Longva, T. Batteries. In Proceedings of the 2nd MTCC Workshop, London, UK, 24 October 2018.

56.	Geng, H. *Data Center Handbook*; John Wiley & Sons: Hoboken, NJ, USA, 2014; ISBN 9781118436639.

57.	Myhre, G.; Shindell, D.; Bréon, F.-M.; Collins, W.; Fuglestvedt, J.; Huang, J.; Koch, D.; Lamarque, J.-F.; Lee, D.; Mendoza, B.; et al. *Climate Change 2013: The Physical Science Basis—Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change*; IPCC (Intergovernmental Panel on Climate Change): Geneva, Switzerland, 2013; p. 714.

58. Feger, D. Gas combustion units: High performance technologies for safe disposal of excess boil off gas on the new generation of LNG carriers. In Proceedings of the 15th International Conference & Exhibition on Liquefied Natural Gas (LNG 15), Barcelona, Spain, 24–27 April 2007.

59. Laugen, L. An Environmental Life Cycle Assessment of LNG and HFO as Marine Fuels. Master's Thesis, NTNU (Norwegian University of Science and Technology), Trondheim, Norway, 2013.

60. Mike, C. (LNG World Shipping). LNG Fuel and the Ship Emissions Debate. Available online: https://www.lngworldshipping.com/news/view,lng-fuel-and-the-ship-emissions-debate_53722.htm (accessed on 16 April 2019).

61. James, J.C.; Heather, T.; James, J.W. *Methane Emissions from Natural Gas Bunkering Operations in the Marine Sector: A Total Fuel Cycle Approach*; U.S. Department of Transportation Maritime Administration: Washington, DC, USA, 21 November 2015.

62. Union of Concerned Scientists (Science for a Healthy Planet and Safer World). How Clean is Your Electric Vehicle? Available online: https://www.ucsusa.org/clean-vehicles/electric-vehicles/ev-emissions-tool (accessed on 3 March 2018).

63. Chretien, L. Drive Green with Mass Energy, Low Carbon Transportation. Presented at the 2018 Massachusetts Sustainable Communities and Campuses Conference, Plymouth, MA, USA, 22 April 2018.

64. Pai, L. LNG REPORT: 143 LNG-Powered Vessels in Operation, 270 to Come (accessed on 17 January 2019). MarineLink. Available online: https://www.marinelink.com/news/lng-report-lngpowered-vessels-operation-461876 (accessed on 7 March 2019).

65. IGU (International Gas Union). *2018 World LNG Report—27th World Gas. Conference Edition*; IGU (International Gas Union): Barcelona, Spain, 2018.