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Strategy for selecting an optimal propulsion system of a liquefied hydrogen tanker

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ABSTRACT

This study proposed a strategy for selecting an optimal propulsion system of a liquefied hydrogen tanker. Four propulsion system options were conceivable depending on whether the hydrogen BOG (boil-off gas) from the cryogenic cargo tanks was used for fuel or not. These options were evaluated in terms of their economic, technological, and environmental feasibilities. The comparison scope included not only main machinery but also the BOG handling system with electric generators. Cost-benefit analysis, life-cycle costing including carbon tax, and an energy efficiency design index were used as measures to compare the four alternative systems. The analytic hierarchy process made scientific decision-making possible. This methodology provided the priority of each attribute through the use of pairwise comparison matrices. Consequently, the propulsion system using LNG with hydrogen BOG recovery was determined to be the optimal alternative. This system was appropriate for the tanker that achieved the highest evaluation score.

Introduction

According to the enhanced international environmental regulations, the energy market is rapidly changing. The Paris Agreement (l'Accord de Paris) was adopted on 12 December 2015. This agreement not only replaces the Kyoto Protocol with a new policy but also derives the consensus from the international society regarding GHGs (greenhouse gases). The 195 countries that discharge c.a. 96% of the global GHG emissions joined the agreement. Developed and developing countries simultaneously participated in the agreement, and 186 countries submitted plans for a GHG reduction target and its contribution [1]. The obligations are expected to be directly strengthened. Industrial sectors that use or develop renewable and clean energies emerge for an environmentally friendly low-carbon economy. The energy-intensive industries, such as the steel, shipping, and marine sectors, need to adopt a strict energy-efficiency policy and its technology for sustainable developments.

Changes in the energy market have a significant impact on the shipping industry. Over 90% of world trade relies on international shipping, transporting eight billion tons of goods annually [2]. Global shipping accounts for 3.3% of GHG emissions [3]. CO_2, SO_X, NO_X, and particulate matters are significant contributors to air pollution at sea [4]. The IMO (International Maritime Organization) declares the ECA (emission control area) and regulates the SO_X emissions from shipping in the Baltic Sea, the North Sea, and the English Channel [3]. SO_X emissions should be less than 0.1% in ECAs

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after January of 2015 and 0.5% at open sea after January of 2020. NO_X emissions also become more stringent than the existing level. After January of 2016, ships must possess Tier III propulsion machinery that satisfies the allowable NO_X emissions based on the revolutions per minute of the machinery [5].

Increasing the development and use of clean fuels to replace fossil fuels has become a trend. Merchant ships using natural gas [6–11] and airplanes using hydrogen fuel are representatives of this trend [3,12,13]. Vehicles that use natural gas, biofuels, hydrogen, or electric batteries are currently commercialized or under development. Wind, tidal, and solar systems and fuel cells are being gradually adopted for commercial power plants [14,15]. The decarbonization of energy is increasing throughout human life [16].

Hydrogen is remarkable as a clean energy source in the foreseeable future. It is a highly flammable gas and produces 28.7 kcal/g calorie and steam without pollutants when burned under atmospheric conditions. From 1920 to present, hydrogen fuel has been proven with respect to its value and safety in a variety of sectors, such as the automobile, marine, aerospace, power generation, and defense industries [16–20]. Recently, hydrogen has exhibited high potential as an alternative fuel in terms of energy security. The EU (European Union) has adopted a climate and energy policy for encouraging research and development of hydrogen and fuel cell technologies. The EU's vision is to achieve GHG emission levels that are 80–95% compared to the 1990 levels by 2050 and to transition the EU to a low-carbon economy. Ninety representative companies launched FCH-JU (The Fuel Cells and Hydrogen Joint Undertaking) and are proceeding to substantially accelerate the development and market introduction of these technologies [3,21]. In the United States, the Department of Energy conducts the H2USA program considering hydrogen and fuel cells; it actively invests in hydrogen infrastructures and expects that 675,000 jobs will be created in the automobile, electric power, medical, food, and electronic industries [3,22]. Meanwhile, the Japanese government announced that the 2020 Tokyo Olympics are the hydrogen Olympics and has hydrogen programs for many application sectors. Japan aims at a CO_2-free energy supply through the use of complementary infrastructures between hydrogen and electricity [3,23,24].

Hydrogen is produced by reforming hydrocarbons or through water electrolysis. Although hydrogen accounts for 75% of all elements in the universe, it forms a variety of compounds, such as water or hydrocarbons, with the other elements. Because primary energy sources are required to obtain hydrogen, it is commonly understood that hydrogen is an energy carrier [3,17,25]. The industrial production of hydrogen is primarily via the steam reforming hydrocarbons, accounting for 96% of hydrogen production, and less often from more energy-intensive methods, such as water electrolysis, accounting for 4% [26]. The reforming process produces greenhouse gases as a by-product; it is necessary to have CCS (carbon capture and storage) technologies for sustainability [27]. There are many research and development programs aimed at producing hydrogen using renewable resources [3,26,28].

Because the cost of hydrogen is highly dependent on the production sites, the long-distance transport between the producer and consumer is essential for economics. It is necessary to have a hydrogen infrastructure for supplying inexpensive hydrogen to vehicles, power generation, and petrochemical processes [3,17,21,29]. The hydrogen transport and storage should be done on a large scale due to its low energy density per volume [17,26,30,31]. The existing hydrogen transport systems are based on pipelines and tube trailers. These systems are for the large-scale users that generally produce hydrogen on site or that are supplied by nearby producers [3]. The dedicated ship carrying liquefied hydrogen should be required for the intercontinental or long-distance transport [24,26].

An LH_2 tanker (liquefied hydrogen tanker) is designed to transport liquefied hydrogen in bulk. Because hydrogen carrier is the term used for the concept of hydrogen storage, it is necessary for the ship carrying liquefied hydrogen in bulk to be called a tanker. Liquefied hydrogen is shipped in cryogenic cargo containers at 20 K (−253.15 °C) and atmospheric conditions. The cargo containment systems must be manufactured using a low-temperature steel that has no brittle fracture. The insulating material should also possess a low thermal conductivity for less boil-off gas (BOG). From 1990s, marine hydrogen transport has become of interest when considering alternative energy. Petersen et al. proposed a liquid hydrogen tanker called SWATH (small-water-plane-area twin hull), which has Type C tanks [30]. For the EQHHP (Euro-Quebec Hydrogen Project), a hydrogen shipping concept was introduced from Canada to Deutschland. The barge-mounted tanker had pressure vessels for storage [32,33]. Wurster et al. presented a barge-based tanker that has fuel cells for the propulsion system [34]. Japanese researchers proposed a catamaran tanker with Type B tanks for the WE-NET program [31]. According to the Japanese energy basic plan, a shipbuilder announced the concept of a CO_2-free hydrogen supply chain. The hydrogen was produced by reforming brown coals and transported by two types of tankers: 160K-Type B tanks and 5K-Type C tanks [23,24]. Although NASA (National Aeronautics and Space Administration) previously supplied liquefied hydrogen using barges for aerospace programs, this process was not commercial transport by shipping [17,35]. As stated above, there was no commercial hydrogen shipping. The previous studies mentioned the technical feasibility and challenges and provided a type of a liquefied hydrogen tanker for the near future; the ship is similar to an LNG (liquefied natural gas) carrier, but the deadweight is lighter than that of the LNG carrier.

One of the main concerns is the propulsion system for liquefied hydrogen tankers. The above studies focused on concepts for hydrogen shipping, but the concerns are inadequate. Generally, the propulsion function of gas carriers is closely related with the utilization of BOG and generation of electric power [7]. LNG carriers, which constitute the majority of gas carriers, have used steam turbine plants for propulsion for decades; this technology is to prevent pressure increases by consuming BOG for safe transport. Although marine engines that comply with maritime environmental regulations have been launched over the past years, merchant ships that include the gas carrier with the engines have been on an increasing trend [36]. An LH_2 tanker is a type of gas carrier and needs to manage the natural hydrogen BOG in the cargo tanks. Such tankers may use the BOG as fuel for propulsion or possess a reliquefaction system that recovers the BOG by consuming a vast amount of power. Many studies have been conducted regarding hydrogen-fueled ships. El Gohary et al. [2] and Ibrahim S. Seddiek et al. [37] discussed the usefulness of hydrogen as a marine fuel for internal combustion engines. Petersen et al. studied some of the findings in terms of the design requirements for barge-mounted hydrogen tanks [30]. Abe et al. reported LH_2 tankers that use hydrogen BOG [31]. Veldhuis et al. addressed the particular technical and economic issues on a high-speed foil-assisted catamaran by using hydrogen fuel for a 600 TEU container ship [4]. Fuel cells are applicable for small-size ships to large carriers. The FellowSHIP project has begun in 2003 to study the potential feasibility of fuel cell technology for an offshore supply vessel [6]. Alkaner and Zhou studied the performance of a molten carbonate fuel cell plant for marine applications considering a life cycle assessment [18]. de-Troya et al. investigated the possible types of fuel cells in terms of their application to ships [19]. Comprehensive reviews of various fuel cells were discussed for the application to ships [20]. The future marine fuel cell market was projected with regards to the history of the marine engine market [38]. The appropriate alternative among the above various technologies should be selected for the optimal propulsion strategy.

This study proposes an optimal propulsion system considering the economic, technical, and environmental aspects of an LH_2 tanker. This system is essential for the hydrogen-supply chain that supports the hydrogen economy. The academic contributions of this study are as follows. First, the potential shipping route is considered between a producer and a consumer. Second, the propulsion systems consider the voyage, anchorage, canal passage, and failure conditions. Third, the economic effects are described depending on hydrogen prices and carbon tax. Fourth, the optimal system is selected using a quantitative decision-making process. Finally, the challenges of this type of propulsion system are discussed. The remainder of this paper is organized as follows. "Description of alternative propulsion systems for liquefied hydrogen tankers" Section describes the alternative propulsion systems. The methodologies for evaluating the performance are explained in "Methodology for performance evaluation" Section. "Assumptions for case studies" Section presents the assumptions of case studies for hydrogen shipping. The final results for the alternatives are described in "Results and discussion" Section. "Conclusions" Section summarizes and concludes this paper.

Description of alternative propulsion systems for liquefied hydrogen tankers

The configuration of the propulsion system for an LH_2 tanker depends on whether the hydrogen BOG is used as fuel or not. The BOG occurs due to imperfect insulation and sloshing in the cargo tanks [7,36]. Because the BOG increases the internal pressure in the cargo tanks, it should be appropriately treated for a safe voyage. Conceivable propulsion systems for LH_2 tankers, as shown in Fig. 1, are as follows.

- System A: Dual-fuel engines that use distillate fuel with the hydrogen BOG condensed in the reliquefaction system,
- System B: Dual-fuel engines that use gas fuel with the hydrogen BOG condensed in the reliquefaction system,
- System C: Steam turbine with boiler that uses hydrogen BOG,
- System D: Molten carbonate fuel cell that uses hydrogen BOG.

Systems A and B consume hydrocarbon fuels rather than hydrogen BOG for driving shafts, as shown in Fig. 1. The fuel is gas fuel (LNG) or distillate fuel (marine gas oil; MGO). The BOG is liquefied in a separate system called a reliquefaction unit and returned to the cargo tanks. This BOG recovery means that no hydrogen is lost through consumption. Because the reliquefaction system is separated from the propulsion system and requires a substantial amount of electric power, electric generators should be equipped [7].

In System C, the steam turbines consume the hydrogen BOG and the hydrocarbon fuel in parallel for the mechanically driven shaft. For conventional LNG carriers, the steam turbines are widely adopted as 71% shares and considered quite reliable [36]. This technology makes BOG handling possible and supplies 100% of the fuel demand; the liquefied hydrogen in tanks may be vaporized if required.

System D generates electricity by consuming the hydrogen BOG in fuel cell stacks. The electric power drives shaft motors for propulsion, as shown in Fig. 1. The fuel cell is a power generation unit in which the chemical reaction between hydrogen and oxygen is converted into electric energy [3]. Fuel cell technology is already utilized as an auxiliary battery or propulsion system for underwater voyages in defense systems. Through mass production, this technology is highlighted as a next-generation propulsion system to replace internal combustion engines [4,37]. Because fuel cells have no emission and noise pollution, they are considered an environmentally friendly technology. The types of fuel cells vary depending on their operating temperature and fuel. The MCFC (molten-carbonate fuel cell) is the proper type of fuel cell for LH_2 tankers that require considerable electric power. The MCFC has been proven to be appropriate for ship prolusion, such as the Viking Lady, which is the first merchant ship to use fuel cells [3,6,18,19].

Methodology for performance evaluation

The optimal propulsion system for the LH_2 tanker may be selected based on the AHP (analytic hierarchy process) considering costs, benefits, and energy efficiency. The ship has four alternative propulsion systems depending on the type of fuel. The configurations of each propulsion system are different. For an impartial comparison, this study considers not only the main propulsion machinery but also a reliquefaction unit that includes power generators [7]. These four systems have different costs and benefits. In addition, a carbon tax is charged concerning the ship's GHG emissions.

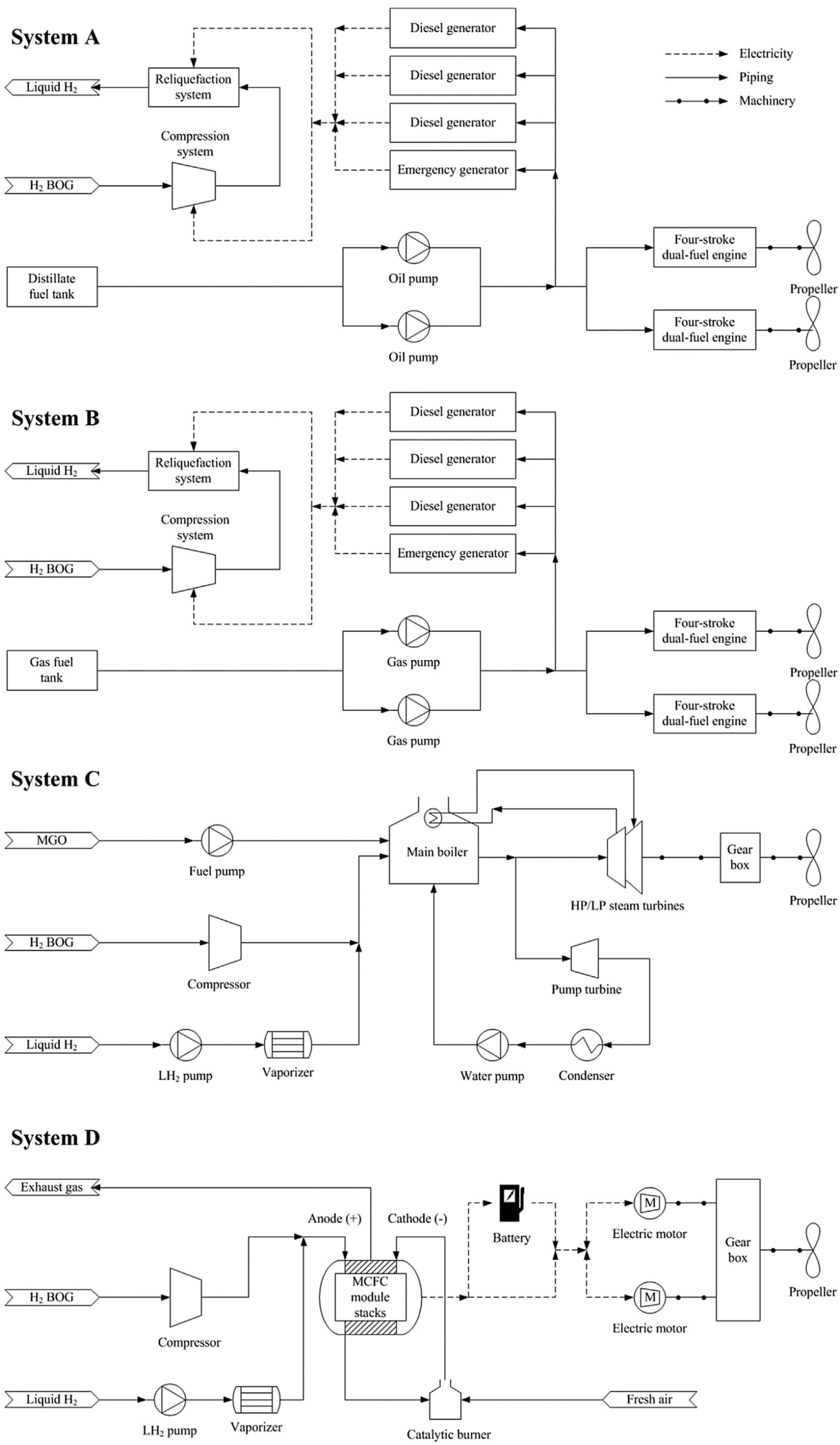

Fig. 1 – Propulsion systems for liquefied hydrogen tanker.

Cost-benefit analysis

Cost-benefit analysis is a technique for estimating and quantitatively comparing all the social costs and benefits for selecting the optimal alternative. This analysis represents the costs and benefits as a price by applying a constant discount rate to estimate the future value compared to the current value. The economic feasibility of the alternative systems is evaluated based on the costs and benefits of an LH_2 tanker where the social discount rate is 5.5% [39].

The B/C ratio (benefit-cost ratio) is the ratio of benefit to cost as present values. This ratio is a comparison standard for decision making. If the B/C ratio is larger than 1.0, then the alternative will be economically feasible [39]. The following equation mathematically presents the B/C ratio.

$$B/C = \sum_{t=0}^{L} \frac{B_t}{(1+r)^t} \Bigg/ \sum_{t=0}^{L} \frac{C_t}{(1+r)^t} \geq 1 \tag{1}$$

here, B_t is the benefit in US$ at t period, C_t is the cost in US$ at t period, r is the discount rate in percent, L is the time span in years, and t is from 0 to 24, respectively.

The NPV (net present value) is estimated by subtracting the cost from the benefit with the discount rate as present values. If the NPV is larger than 0, the alternative will be economically feasible. Equation (2) shows the mathematical formulation of the NPV.

$$NPV = \sum_{t=0}^{L} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{L} \frac{C_t}{(1+r)^t} \geq 0 \tag{2}$$

The IRR (internal rate of return), s is calculated as the rate of return that can equalize the benefits and costs in equation (3). It is used to evaluate the necessity of capital investments. A higher value corresponds to higher profits.

$$IRR \geq s, \ where \ \sum_{t=0}^{L} \frac{B_t}{(1+s)^t} = \sum_{t=0}^{L} \frac{C_t}{(1+s)^t} \tag{3}$$

Herein, the cost is estimated as the life-cycle cost, and the benefit is the freight revenue of an LH_2 tanker.

Life-cycle costing

LCC (life-cycle cost) refers to the total ownership cost during the lifetime of a system [40]. This cost is the cost of an LH_2 tanker, including planning, design, construction, operation, maintenance, labor, tax, and insurance. The LCC is the sum of CAPEX (capital expenditures), OPEX (operating expenditures), and RISKEX (risk expenditure), as shown in equation (4). The CAPEX is only considered at first year for estimating LCC.

$$LCC = \sum_{t=0}^{L} \frac{C_t}{(1+r)^t} = CAPEX|_{t=0} + \sum_{t=0}^{L} \left(\frac{OPEX_t + RISKEX_t}{(1+r)^t} \right) \tag{4}$$

To evaluate the economy of the ship, comparative LCC is an appropriate measurement [7,8]. Because the system configuration depends on its fuel type, the scope of consideration includes CAPEX, OPEX, and RISKEX for an unbiased comparison. All the costs are based on LNG carriers because the LH_2 tanker is similar to the LNG carrier but has no reference [30,31]. The lifetime is 25 years.

The CAPEX differs in the configuration of the propulsion system. A 140 K m^3 LNG carrier equipped with a reliquefaction system has 200 MUS$ (million US dollars) for CAPEX [41]. This value may be the CAPEX of System A shown in Fig. 1. System B has a configuration similar to that of System A, but it needs to have an independent LNG tank; the CAPEX of System B is 206 MUS$. Because the costs per unit power of a steam turbine and boiler are 134 US$/kW and 244 US$/kW, respectively [42], System C costs 192 MUS$. System D possesses an MCFC that will cost 800 US$/kW in 2020 [38]; the CAPEX is 202 MUS$. Table 1 summarizes the cost breakdown of the four alternative systems.

The annual OPEX is the sum of maintenance, labor, and fuel costs as well as carbon tax, as shown in equation (5).

$$OPEX = C_M + C_{CREW} + C_P + C_R + C_{CO_2} \tag{5}$$

The maintenance costs for propulsion and reliquefaction systems, C_M, are 5% of each CAPEX. The number of crew members is 28 persons, and their labor costs are 1.3 MUS$/year [34]. The fuel costs consider both propulsion and reliquefaction systems. Fig. 2 illustrates the estimated fluctuation of fuel prices [3,43–45].

Equations (5A) and (5B) present the fuel costs for propulsion and reliquefaction, respectively.

$$C_P = T_P \cdot f \cdot C_f \tag{5A}$$

here, T_P is the annual operation time of the propulsion system in h/year, f is the fuel consumption per unit time in ton/h, and C_f is the specific fuel price in US$/ton, respectively.

$$C_R = T_R \cdot f \cdot C_f \tag{5B}$$

here, T_R is the annual operation time of the reliquefaction system in h/year, f is the fuel consumption per time unit time in ton/h, and C_f is the specific fuel price in US$/ton, respectively.

The carbon tax must be based on the total carbon dioxide emissions of a ship. The carbon generations may be calculated from the shipping energy efficiency. The IMF (International Monetary Fund) proposed a carbon pricing for international aviation and marine shipping of 30 US$/ton-$CO_2$ for the climate finance [1]. Equation (5C) shows the carbon tax:

$$C_{CO_2} = m_{CO_2} \cdot R_{Tax} \cdot N_{Voyage} \tag{5C}$$

here, m_{CO_2} is the carbon dioxide generated per round trip in

Table 1 – Cost breakdown of equipment for propulsion systems.

Machinery	Price, US$
Four-stroke DF engine	2,450,000
Feed pump	921,000
Diesel generator	1,400,000
LNG tank	5,500,000
Boiler	6,832,000
Steam turbine	3,752,000
Water system	200,000
Vaporizer	150,000
Compressor	1,145,000
MCFC module stacks	22,400,000
Reliquefaction system	3,899,100

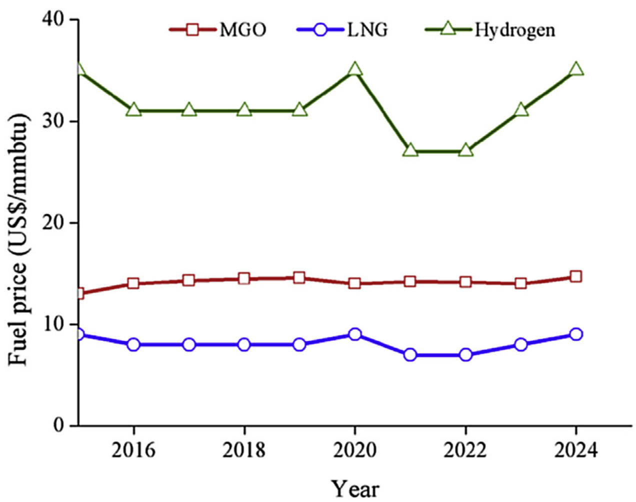

Fig. 2 – Global fuel prices: MGO, LNG, and hydrogen.

ton/trip, R_{Tax} is the specific charge of carbon dioxide in US$/ton, and N_{Voyage} is annual number of round trips in trip/year, respectively.

The annual RISKEX is the sum of freight damage and repair costs due to the propulsion or reliquefaction system, as follows:

$$RISKEX = D_P + D_R + D_{FIX} \tag{6}$$

The freight damage due to propulsion failures considers the unavailability, transportation, and freight charge in equation (6A). Ten percent of the cargo hydrogen price is the freight charge [24].

$$D_P = (1 - A_P) \cdot M_{LH_2} \cdot C_{Freight} \tag{6A}$$

here, A_P is the availability of the propulsion system, M_{LH_2} is the annual transportation of liquid hydrogen in ton/year, and $C_{Freight}$ is the freight charge of liquid hydrogen in US$/ton, respectively.

The freight damage due to reliquefaction failures considers the unavailability, BOG generation, and the cargo hydrogen price as the following equation (6B):

$$D_R = (1 - A_R) \cdot m_{BOG} \cdot C_{LH_2} \tag{6B}$$

here, A_R is the availability of the reliquefaction system, m_{BOG} is the annual BOG generation of liquid hydrogen in ton/year, and C_{LH_2} is the hydrogen cost in US$/ton, respectively.

The repair cost considers the unavailability, criticality, man-hour, and labor cost for each failure component in equation (6C).

$$D_{FIX} = \sum_i (1 - A_i) \cdot P_{i-th,cr} \cdot MH_i \cdot C_{Labor} \tag{6C}$$

here, A_i is the availability of the *i-th* component of the propulsion or reliquefaction systems, $P_{i\text{-}th,cr}$ is the criticality of the *i-th* component of the propulsion or reliquefaction systems, MH_i is the man-hour for repairing the *i-th* component of the propulsion or reliquefaction systems in h, and C_{Labor} is the labor cost of repair in US$/h, respectively.

RISKEX calculations utilize a RBD (reliability block diagram). Fig. 3 presents the RBDs of the four alternative systems. Systems A and B are required to consider the availability of propulsion and reliquefaction systems separately. Systems C and D have no reliquefaction system, which implies that no consideration of the freight damage is required. Because the fuel cells in System D have little operation records, the stacks are considered to be a reactor. The LH_2 tanker will have a brand new system. It is difficult to obtain reliable information for a reliability database. Herein, the OREDA (offshore and onshore reliability data) are used to calculate availability [46]. Table 2 presents the reliability information of the system components.

Energy efficiency design index

The energy efficiency of a system is the ratio of the energy input and output. The energy efficiency for shipping is defined as the fuel consumption to achieve transporting work. It depends on the types of ship, equipment, configuration, and fuel. The SNAME (Society of Naval Architects and Marine Engineers) and SIGTTO (Society of International Gas Tanker and Terminal Operators) proposed the concept of an energy efficiency design index for LNG carriers equipped with a dual-fuel engine and low-speed engine including a reliquefaction unit, respectively [36].

The IMO adopted the EEDI (energy efficiency design index) to evaluate the energy efficiency of a newly built ship in July 2011 [47]. The EEDI as a mandatory requirement is a technical indicator regarding the energy efficiency of equipment and machinery. It evaluates the CO_2 emissions per transported distance depending on ship type. The reference value of the required EEDI is gradually being strengthened: Phase 1 is from January 2015 to December 2019, Phase 2 is from January 2020 to December 2024, and Phase 3 is after January 2025 [47].

The EEDI for an LH_2 tanker refers to an LNG carrier in equations (7) and (8). The attained EEDI must be lower than the reference value.

$$\textit{Reference value} = 2253.7 \times (DWT)^{-0.474} \tag{7}$$

$$EEDI = \frac{P_{ME} \times (C_{F,Pilot} \times SFC_{ME,Pilot} + C_{F,Fuel} SFC_{ME,Fuel})}{f_c \times V_{Ref} \times DWT} + \frac{P_{AE} \times (C_{F,Pilot} \times SFC_{AE,Pilot} + C_{F,Fuel} SFC_{AE,Fuel})}{f_c \times V_{Ref} \times DWT} \tag{8}$$

$$P_{ME} = 0.75 \times MCR \quad \text{for dual}-\text{fuel engine} \tag{9}$$

$$P_{ST} = 0.83 \times MCR \quad \text{for steam turbine} \tag{10}$$

If an LH_2 tanker contains reliquefaction equipment, P_{AE} will include $P_{AE,Reliq}$ for the EEDI calculation in equations (11)–(14).

$$P_{AE} = 0.025 \times MCR + 250 + P_{AE,Reliq.} \tag{11}$$

$$P_{AE,Reliq.} = V_{Cargo} \times BOR \times COP_{Reliq.} \tag{12}$$

$$BOR = \left(\frac{Q}{H_{Latent}} \times 3600 \times 24\right) \times \frac{100}{\rho_{LH_2} V_{Cargo}} \tag{13}$$

$$COP_{Reliq.} = \frac{\rho_{LH_2} \times H_{Latent}}{24 \times 3600 \times COP_{cooling}} \tag{14}$$

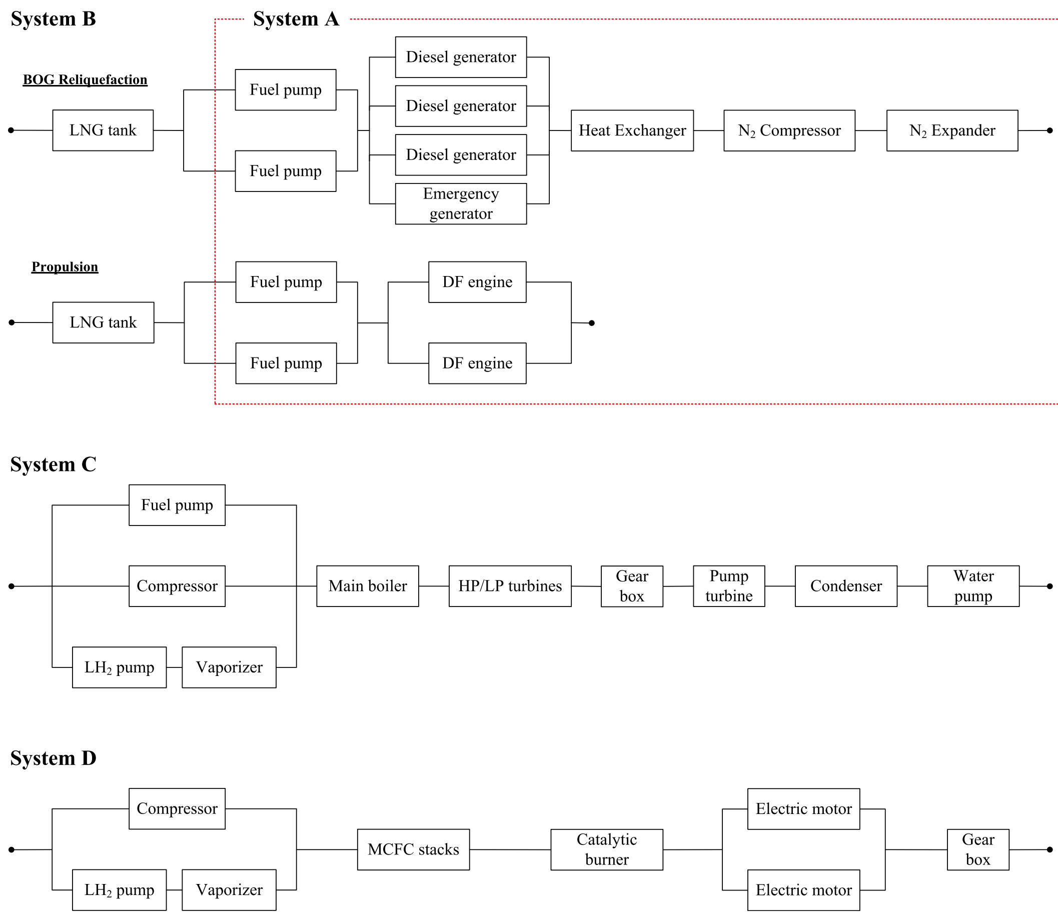

Fig. 3 – Reliability block diagrams of propulsion systems for liquefied hydrogen tanker.

If the gas carrier is the direct-diesel-driven type, then the cubic capacity correction factor in equation (15) will be applied. Here, R is defined by dividing the deadweight into the cargo capacity; otherwise, the factor is 1.

$$f_c = R^{-0.56} \quad (15)$$

Table 2 – Reliability data of failure rate, repair time, and man-hour.

Component	Failure rate, per 10^6 h	Active repair time, h	Man-hour, h
Four-stroke DF engine	54.94	10	21
Oil pump	72.01	20	48
Gas pump	10.09	11	11
Diesel generator	30.04	27	35
LNG tank	30.13	8.2	12
Heat exchanger	17.31	47	112
Compressor	194.4	16	30
Expander	12.68	16	390
Boiler	450.59	25	25
Steam turbine	101.16	9.5	9.5
Water pump	39.93	69	69
Water pump, turbine	69.55	120	120
Vaporizer	17.31	47	47
Gear box	1.5	0.1	0.1
MCFC module	30.13	8.2	8.2
Catalytic burner	62.45	14	14
Battery	8.95	42	42
Electric motor	25.04	24	24

Analytic hierarchy process

The AHP (analytic hierarchy process) is a decision-making technique for achieving the optimal alternative considering diverse criteria. It is necessary to identify attributes of each item and establish standards for evaluating an alternative. The AHP proposed by Thomas L. Saaty creates a homogeneous cluster of the alternatives and attributes, hierarchizes each level, and assigns the weight factor for decision making [48]. In particular, AHP is widely used for decision making on the basis of the cost-benefit analysis [48–50]. The AHP provides the reasonable and intuitive optimum. A decision maker may prepare the pairwise comparison matrix of each attribute and calculate the priority vector using eigenvalue decomposition [51]. Fig. 4 illustrates the hierarchy model for the alternative systems and attributes of an LH_2 tanker.

The AHP has distinct advantages compared with the other techniques. It provides the consistency index in equation (16) for evaluating the consistency after deriving the priority. A higher consistency index implies that the estimate has logical inconsistency.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (16)$$

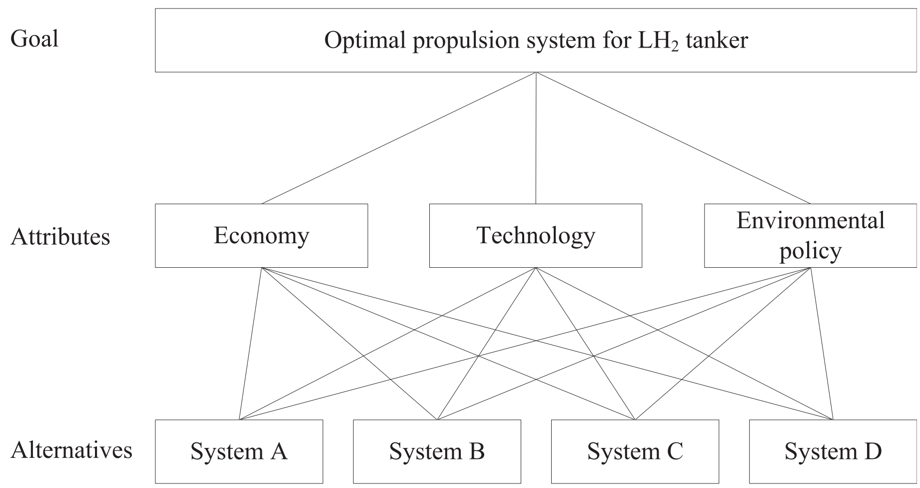

Fig. 4 – Hierarchy model for evaluating attributes and alternatives.

here, CI is the consistency index, λ_{max} is the maximum eigenvalue, and n is the number of attributes, respectively.

The consistency ratio provides verification of the consistency index in equation (17). When the ratio is less than 0.1, the derived priority is a consistent and reliable result.

$$CR = \frac{CI}{RI} \tag{17}$$

here, CR is the consistency ratio and RI is the random consistency index, respectively.

The scale of priority is normally one to nine for pairwise comparison matrices. This scale range has been proven in many sectors and is justified for comparing homogeneous elements [48]. The optimal alternative may have a higher AHP score than the other alternatives. A decision maker chooses whether to implement the optimal alternative.

Assumptions for case studies

The LH_2 tanker travels between Yanbu and Rotterdam. Because Saudi Arabia has abundant hydrocarbon, photovoltaic, and solar resources, Yanbu is a potential area for the mass production of hydrogen. France, Belgium, the Netherlands, and Norway are potential areas of high hydrogen consumption due to their use of hydrogen vehicles because of environmental regulations. Rotterdam is the proper location for the LH_2 tanker because it is the most active port in Europe [52]. Fig. 5 shows the shipping route and the present ECA and potential ECA.

The transport capacity of one tanker is 140 K m^3, which is similar to the capacity of a large LNG carrier. According to the EC (European Commission), the European consumption of hydrogen will approach 3.5 M ton/year (10 MTOE/year) in 2020 and 17.5 M ton/year (50 MTOE/year) [19,24]. The consumption is 137 K m^3/day by converting 3.5 M ton/year in 2020. From this perspective, the LH_2 tanker should have a capacity of 140 K m^3, and its fleet must consist of 20 ships.

Because an LNG carrier transports cryogenic LNG, which bears similarity with liquefied hydrogen, the LH_2 tanker is considered to possess the same capacity as the LNG carrier [24,30,31]. The principal features of the LNG carrier, such as hull structures, cargo tanks, insulation layers, and BOG handling techniques, may be applicable for the LH_2 tanker after modifications.

The cargo tanks are prismatic pressure vessels as IMO Type C [53]. The cargo containment type has a hull-fit shape; this advantage is to manufacture a tank that appears to be a membrane tank. Moreover, the tank withstands the pressure increase due to hydrogen BOG. The tank material is stainless steel (k = 2 W/m-K), while the insulation layers use vacuum perlite (k = 0.002 W/m-K) for minimizing the BOG [23,24]. The BOR (boil-off rate) is estimated by using both heat transfer coefficients in equation (13): 0.216%/day. The cargo tanks maintain liquefied hydrogen as 10% of their capacity; this is necessary to maintain the internal conditions and to use the BOG as fuel. Table 3 summarizes the specifications of the LH_2 tanker.

The voyage scenario should consider the route, waters, and operation times of the propulsion and reliquefaction systems, as shown in Table 4. The voyage conditions are distinguished into laden and ballast. Both voyages go through sea going, anchoring, and canal passing. Both systems run while on voyage, but the reliquefaction system runs only while on anchoring. If the tanker stays at a port, no system will be operated. It takes approximately 10 days from departure to arrival.

The system specifications and fuel property are described in Tables 5 and 6. Systems A, B, and D use one type of fuel: MGO, LNG, and hydrogen. System C uses hydrogen BOG at ECAs and MGO at the other seas. The fuel prices refer to the values in mass in Fig. 2; these prices are projected on the basis of the present prices and fluctuations [43,44]. After 2025, the fuel prices are the same as those in 2024. MGO, LNG, and hydrogen prices are 567 US$/ton, 443 US$/ton, and 4000 US$/ton in 2020, respectively. Herein, the hydrogen fuel price excludes the freight charge due to the BOG use by the LH_2 tanker.

Results and discussion

Although all the alternative systems are available for the LH_2 tanker, they must be supported with respect to their

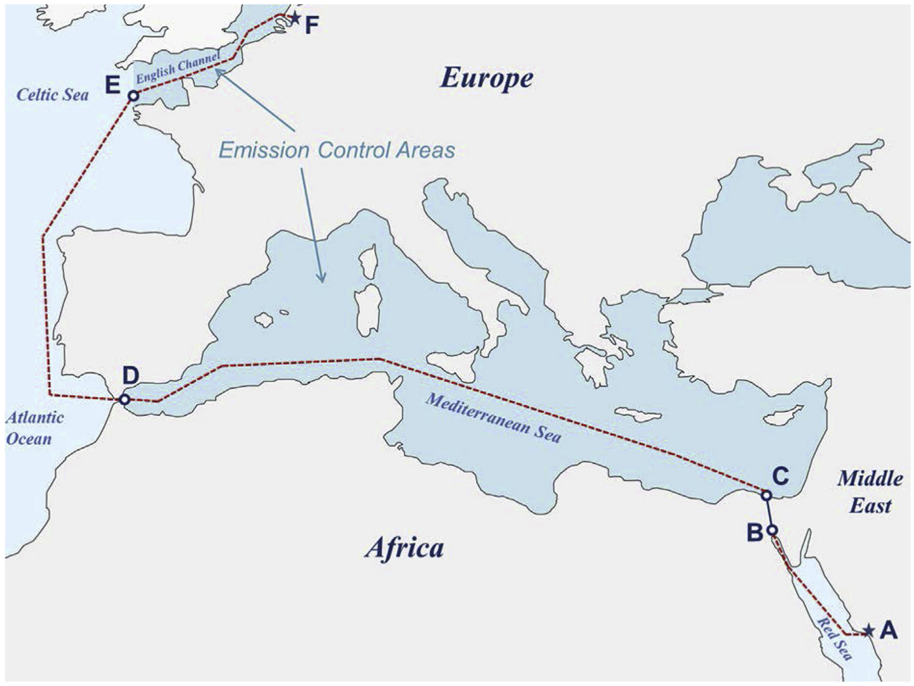

Fig. 5 – Shipping route of liquefied hydrogen tanker.

Table 3 – Specifications of liquefied hydrogen tanker.

Ship particulars	Unit	Value
Ship type	–	Gas carrier
Deadweight (DWT)	Ton	27,600
Principal dimensions	m	284 (L) × 43 (B) × 25 (D)
Service speed	Knots	20
Cargo tank capacity	m^3	140,000
Voyage route	–	Yanbu ↔ Rotterdam
Voyage distance	NM	3900
Number of bunkering operations	EA	2
Ports for bunkering	–	Yanbu, Rotterdam

economic, technological, and environmental feasibilities. The results and relevant issues are described in the following.

Cost-benefit

To determine the economic feasibility of each alternative, the LCC, B/C ratio, NPV and IRR over the lifetime are compared. Each CAPEX and RISKEX is almost identical, but the OPEX is substantially different, as shown in Fig. 6 (A). Because the hydrogen fuel is quite expensive, Systems C and D that use hydrogen have higher OPEXs than Systems A and B that use hydrocarbons.

Table 4 – Voyage scenario for liquefied hydrogen tanker.

Voyage	Route	ECA	Operation condition	Time, h		
				Voyage	Propulsion	BOG generation
Laden	A	No	LH_2 loading, fuel bunkering	24	–	–
	A–B	No	Sea going	23	23	23
	B	No	Anchoring	10	–	10
	B–C	No	Canal passing	14	14	14
	C–D	Yes	Sea going	97	97	97
	D–E	No	Sea going	51	51	51
	E–F	Yes	Sea going	19	19	19
Ballast	F	Yes	LH_2 unloading, fuel bunkering	24	–	–
	F–E	Yes	Sea going	19	19	19
	E–D	No	Sea going	51	51	51
	D–C	Yes	Sea going	97	97	97
	C	No	Anchoring	10	–	10
	C–B	No	Canal passing	14	14	14
	B–A	No	Sea going	23	23	23
Total			Round-trip, h	476	408	428
			Round-trip, day	20	17	18

Table 5 – System specifications for propulsion type.

Item	Unit	BOG recovery		BOG as fuel	
Alternative	–	System A	System B	System C	System D
Propulsion machinery	–	DF engine[a]	DF engine	ST with boiler[b]	Fuel cells[c]
Fuel type		MGO	LNG	MGO/H_2	H_2
Power output per each machinery	kW/EA	14,000	14,000	28,000	500
Revolution speed of each machinery	rpm	514	514	83	–
No. of machinery	EA	2	2	1	56
Specific fuel consumption	g/kWh	180	158	102/95	75
Fuel consumption rate	ton/h	5.04	4.43	2.87/2.65	2.10

[a] DF engine: dual-fuel engine using marine gas oil or liquefied natural gas.
[b] ST with boiler: steam turbine with boiler.
[c] Fuel cells: molten carbonate fuel cells.

Table 6 – Fuel properties for propulsion.

Property item	Unit	MGO	LNG	Hydrogen
Molecular weight	g/mol	≤110	16.04	2.0
Density	kg/m^3	890	444	70.63
Boiling point	°C	175–600	−160	−253
Lower heating value	MJ/kg	42.7	48.6	120
Latent heat	kJ/kg	–	511	443

Table 7 – Availability of propulsion and reliquefaction systems.

Availability	System A	System B	System C	System D
Propulsion, A_P	0.999	0.999	0.979	0.999
Reliquefaction, A_R	0.994	0.994	–	–

The fuel cost substantially accounts for the OPEX in terms of the LCC in Fig. 6 (B). The maintenance and labor costs and carbon tax are not considerably different. The carbon tax is charged on Systems A, B, and C but not on System D.

System C has a higher RISKEX in Fig. 6 (C) and lower availability in Table 7 than the other systems; the boiler and steam turbines have relatively high failure rates. System C needs to have an active maintenance policy. Although Systems A and B cause more freight damage due to reliquefaction failures rather than propulsion failures, the repair cost is relatively inexpensive. The low repair cost means that it takes less time to repair. System D causes few failures and low repair cost due to the high availability.

The B/C ratios are 1.55, 1.92, 1.33, and 0.88 for Systems A, B, C, and D, respectively. System D has a B/C ratio lower than 1.0, implying that this system has no economic feasibility. The other alternatives have economic feasibility because their B/C ratios are higher than 1.0. System B is the most economical alternative. The profits as NPV are 316 MUS$, 428 MUS$, 219 MUS$, and −119 MUS$ and the IRRs are 20.64%, 26.11%,

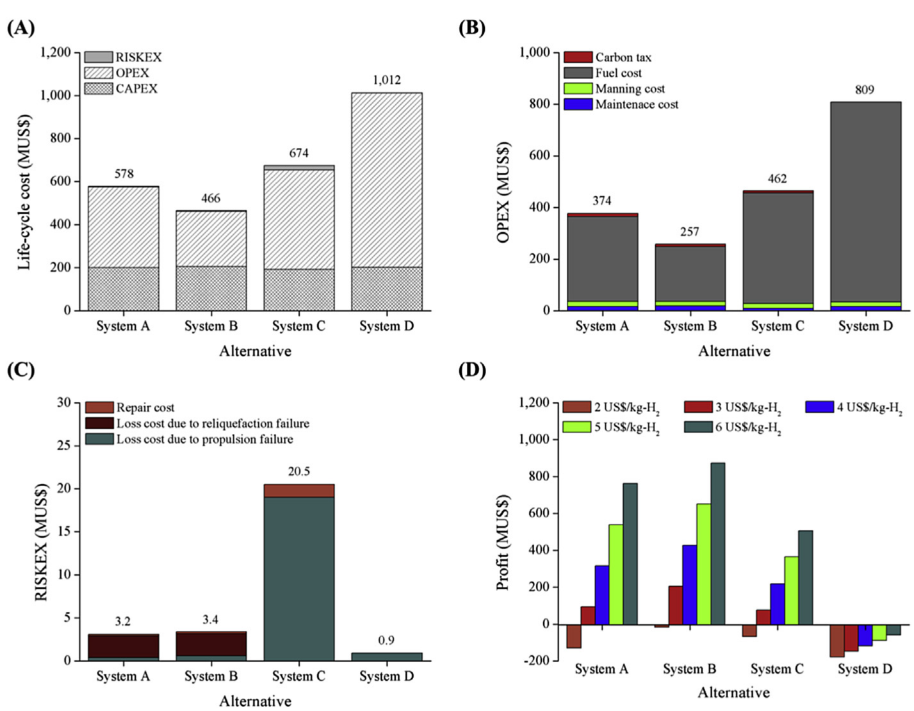

Fig. 6 – Life-cycle cost, OPEX, RISKEX, and profit of propulsion systems.

16.68%, and −2.24% for Systems A, B, C, and D, respectively. These results show the same tread as the B/C ratio and also confirm that the most economic system with the highest IRR is System B. Therefore, System B, A, and C are competitive alternatives in order of economic feasibility. The reason for the deficiency of System D is the expensive hydrogen price. Many studies expect the potential price of hydrogen to be 2 to 4 US$/kg [3,43–45]. Considering the price, System B creates higher profits, while System D causes a deficit.

The hydrogen price for which each alternative creates a profit is 2.6 US$/kg, 2.09 US$/kg, 2.16 US$/kg, and 6.2 US$/kg for Systems A, B, C, and D, respectively; the B/C ratios are larger than 1.0. These prices are the marginal prices of hydrogen shipping. The results imply that Systems A, B, and C are applicable alternatives at low prices. System D is the impractical alternative due to the use of fuel cells. Because hydrogen is an uncompetitive fuel, it demands an incentive.

How much is the realistic incentive for System D using hydrogen fuel during the lifetime? The percentages of the incentive that should be supported for a ship owner are as follows:

- If the hydrogen price is 2 US$/kg, 41% of the fuel cost will be required;
- If the hydrogen price is 3 US$/kg, 27% of the fuel cost will be required;
- If the hydrogen price is 4 US$/kg, 15% of the fuel cost will be required.

Meanwhile, the LH_2 tanker with System D may have economic feasibility during its lifetime if different incentives of 50%, 40%, 30%, 20%, and 10% of the fuel cost are given annually from 2020 to 2024. No incentive is needed after 2025.

Energy efficiency design index

The attained EEDI depends on the fuel types: 17.47, 14.35, 14, and 0 for Systems A, B, C, and D, respectively, as shown in Fig. 7. The LH_2 tanker that runs from 2020 must satisfy the reference EEDI, 14.45, by Phase 2. With the exception of System A, the other alternatives comply with the reference value. After 2025, the reference value decreases to 12.64 by Phase 3. Newly constructed tankers have to be designed to markedly reduce the generation of carbon dioxide.

The present EEDI calculation is aimed at newly built ships. It has inadequate aspects for the phase reinforced. For instance, although LH_2 tankers with Systems B and C as built in 2020 comply with Phase 2, these tankers may not satisfy the reference value by Phase 3. The EEOI (energy efficiency operational indicator) may be appropriate for managing CO_2 emissions for operational ships [54].

Analytic hierarchy process

The AHP applies four alternatives and three attributes. The scale of priority is assigned to the individual pairwise comparison matrix. Tables 8–11 show the preferences and priorities for each attribute.

The B/C ratio, NPV, and IRR indicate that the most preferred alternative is System B in terms of economic feasibility. For AHP, regarding the economy, System B is strongly preferred over Systems A, C, and D, and 4, 1/2, and 1/6 are entered in the first column in Table 8.

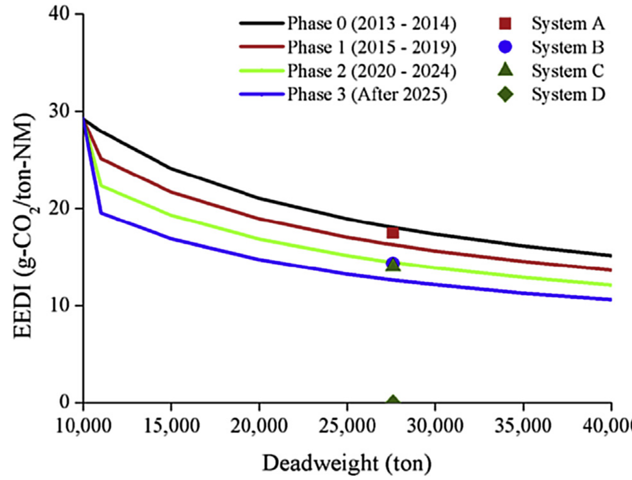

Fig. 7 – Deadweight and energy efficiency design index for propulsion systems.

For the propulsion systems in gas carriers, a marine diesel-electric system has a higher preference than steam turbines or other technologies in future orders [36]. The marine diesel-electric engine with reliquefaction plant accounts for an 81% market share. However, the steam turbines occupy a 9% share. According to this implication, Systems A and B have the higher preferences than Systems C and D. Because System A has no independent LNG tank, System A is relatively simpler than System B in terms of system configurations; therefore, the priority of System A is higher than that of System B. System D, however, is a new technology and has few references for marine propulsion. The priority of System D is lower than that of System C. Regarding the technology System A has 2, 4, and 7 times the preferences of Systems B, C, and D, respectively, as shown in Table 9.

For the environmental policy, the EEDI is used for assigning the priority in the AHP. Considering EEDI Phase 2 in Fig. 7, Systems C and D have slightly higher priorities than System B. System B has 1/5 times the preferences of Systems C and D; Systems C and D have a few differences in terms of the preferences in Table 10.

Table 11 shows that the economy has 3 times the preference of the technology, whereas the technology has 2 times the preferences of the environmental policy. All of the consistency ratios are less than 0.1, and there is no need to explore the inconsistencies in the matrices.

Regarding the priorities in the pairwise comparison matrices, Table 12 presents the final AHP scores for the alternative systems. The economic aspect has the highest priority, whereas the preferred technology and environmental aspect have relatively low priorities. System B is the most optimal for the LH_2 tanker with a high AHP score of 0.448. The tanker with System B satisfies the requirements of economic, technological, and environmental feasibilities.

Table 8 – Pairwise comparison matrix for four alternatives using economy.

Economy	System A	System B	System C	System D	Priority vector
System A	1.00	0.25	2.00	6.00	4.152
System B	4.00	1.00	5.00	7.00	4.150
System C	0.50	0.20	1.00	3.00	4.149
System D	0.17	0.14	0.33	1.00	4.143

$\lambda_{max} = 4.148$; $CI = 0.0495$; $CR = 0.055$.

Table 9 – Pairwise comparison matrix for four alternatives using technology.

Technology	System A	System B	System C	System D	Priority vector
System A	1.00	2.00	4.00	7.00	4.008
System B	0.50	1.00	2.00	3.00	4.008
System C	0.25	0.50	1.00	2.00	4.008
System D	0.14	0.33	0.50	1.00	4.008

$\lambda_{max} = 4.008$; $CI = 0.003$; $CR = 0.003$.

Table 10 – Pairwise comparison matrix for four alternatives using environmental policy.

Environment	System A	System B	System C	System D	Priority vector
System A	1.00	0.50	0.20	0.20	4.119
System B	2.00	1.00	0.20	0.20	4.119
System C	5.00	5.00	1.00	0.50	4.124
System D	5.00	5.00	2.00	1.00	4.124

$\lambda_{max} = 4.121$; $CI = 0.040$; $CR = 0.045$.

Table 11 – Pairwise comparison matrix for three attributes.

Attributes	Economy	Technology	Environment	Priority vector
Economy	1.00	3.00	4.00	3.018
Technology	0.33	1.00	2.00	3.018
Environment	0.25	0.50	1.00	3.018

$\lambda_{max} = 3.018$; $CI = 0.009$; $CR = 0.018$.

Table 12 – Final priority vector using AHP.

Propulsion systems	Economy (0.625)	Technology (0.238)	Environment (0.137)	Priority vector
System A	0.225	0.531	0.069	0.277
System B	0.599	0.256	0.098	0.448
System C	0.124	0.137	0.345	0.157
System D	0.052	0.076	0.488	0.118

Conclusions

This study proposed the optimal propulsion system for a liquefied hydrogen tanker. The applicable alternatives were evaluated with regard to economic, technological, and environmental aspects for shipping. For reasonable decision making, the analytic hierarchy process was applied to the selection of the optimal system. The costs and benefits were compared in terms of the benefit-cost ratio, net present value, life-cycle cost, and internal rate of return. The energy efficiency design index was employed to evaluate the suitability of green-house gas emissions from the alternatives.

The OPEX accounted for the main portion of the life-cycle cost. System B resulted in the lowest OPEX, but System D possessed the highest OPEX. The majority of the OPEX was the fuel cost while maintenance and labor costs and carbon tax were insignificant. The RISKEX was very low in the life-cycle cost. Systems A and B provided the same RISKEX levels. System C had the highest RISKEX, but System D caused the lowest RISKEX; the components affected the system availability.

The benefit-cost ratio, net present value, and internal rate of return related to the life-cycle cost. If the costs were low, the profits would be high. Except for System D, the other alternatives had economic feasibility, in which the benefit-cost ratio, net present value, and internal rate of return were positive. In particular, System B was the most economical propulsion system. System D should receive a hydrogen fuel incentive or needed to combine turbo machinery for effective propulsion systems.

The energy efficiency design index represented the relation between fuel consumption and green-house gas emissions. System A exceeded the reference value and was unqualified as a propulsion system; the tanker using MGO needed to have an effective energy system. Systems B, C, and D complied with the reference value of Phase 2. However, these systems did not satisfy the reference value of Phase 3. The energy efficiency operational indicator might be considered for managing greenhouse gas emissions. System C would satisfy the energy efficiency design index of Phase 3 if additional hydrogen was used.

The analytic hierarchy process was introduced to select the optimal system. The pairwise comparison matrices were constructed considering attributes such as economic, technological, and environmental aspects. The optimal system had the highest AHP score. Systems B and C were available alternatives for the tanker with regard to economic feasibility and environmental policy. System B had a higher AHP score than System C, which means that System C is the optimal propulsion system for the liquefied hydrogen tanker.

The results of this paper will be a good guideline for further developments of a liquefied hydrogen tanker. Because this study was an economic evaluation of a liquefied hydrogen tanker on the basis of an LNG carrier, it contained uncertainty in the costing process. The OPEX might be subject to larger uncertainties than the CAPEX. The detailed ship design and operation records may resolve these issues.

The liquefied hydrogen tanker is the major part of a hydrogen-supply chain. It is necessary to study the entire supply chain to evaluate the hydrogen economy and environmental sustainability. The raw material, production process, storage, and transport of hydrogen producers, ports, and infrastructures must be assessed.

Acknowledgments

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Nomenclature

A_i	availability of *i-th* component
A_P	availability of propulsion system
A_R	availability of reliquefaction system
B_t	benefit at *t* period in US$
BOR	boil-off rate in %/day
C_{CO_2}	carbon tax
$C_{F,Fuel}$	non-dimensional conversion factor between fuel consumption and CO_2 emission
$C_{F,Pilot}$	non-dimensional conversion factor between pilot fuel consumption and CO_2 emission
C_{CREW}	labor cost in US$/year
$C_{Freight}$	Freight charge of hydrogen cargo in US$/ton
C_f	Specific fuel price in US$/ton
C_{Labor}	Labor cost in US$/h
C_{LH_2}	Hydrogen cost in US$/ton
C_M	Maintenance cost in US$
C_P	Fuel cost of propulsion system in US$
C_R	Fuel cost of reliquefaction system in US$
C_t	Cost at *t* period in US$
CI	Consistency index
$COP_{cooling}$	Coefficient of design performance of reliquefaction and 0.166
$COP_{Reliq.}$	Coefficient of design power performance of reliquefying BOG
CR	Consistency ratio
D_{FIX}	Repair cost in US$/year
D_P	freight damage due to propulsion failure in US$/year
D_R	freight damage due to reliquefaction failure in US$/year
DWT	deadweight in tons
f	fuel consumption per unit time in ton/h
f_c	the cubic capacity correction factor for gas carriers having direct-diesel-driven propulsion systems
H_{Latent}	latent heat in kJ/kg
L	time span in years
MCR	maximum continue rating in kW
MH_i	man-hour for repair of *i-th* component
M_{LH_2}	annual transportation of liquid hydrogen
m_{BOG}	annual BOG generation of liquid hydrogen
m_{CO_2}	carbon dioxide generation per round trip in ton/trip
N_{Voyage}	annual number of round trips in trip/year
n	number of attributes
$P_{i\text{-}th,cr}$	criticality for *i-th* component
P_{AE}	power of auxiliary engines including propulsion machinery and accommodation in kW
$P_{AE,Reliq.}$	power of auxiliary engine for a reliquefaction system in kW
P_{ME}	power of the main engines, steam turbine, or fuel cells in kW
Q	heat transfer rate in kW
R	the capacity ratio of the deadweight of the ship divided by the total cubic capacity of the cargo tanks
R_{Tax}	specific charge of carbon dioxide in US$/ton
RI	random consistency index
r	social discount rate in %
s	internal rate of return in %
$SFC_{AE,Fuel}$	specific fuel consumption of fuel for auxiliary engine in g/kWh
$SFC_{AE,Pilot}$	specific fuel consumption of pilot fuel for auxiliary engine in g/kWh
$SFC_{ME,Fuel}$	specific fuel consumption of fuel for main engine in g/kWh
$SFC_{ME,Pilot}$	specific fuel consumption of pilot fuel for main engine, steam turbine, or fuel cells g/kWh

T_P	annual operation time of propulsion system in h/year
T_R	annual operation time of reliquefaction system in h/year
t	time order from 0 to 24
V_{Cargo}	cargo tank capacity in m^3
V_{Ref}	service speed in knots

Abbreviations

AHP	analytic hierarchy process
B/C	benefit-cost ratio
BOG	boil-off gas
CAPEX	capital expenditure
CCS	carbon capture and storage
CO_2	carbon dioxide
DF	dual fuel
ECA	emission control area
EEDI	energy efficiency design index
EEOI	energy efficiency operational indicator
GHG	greenhouse gases
IRR	internal rate of return
LCC	life-cycle cost
LH_2	liquefied hydrogen or liquid hydrogen
LNG	liquefied natural gas
MCFC	molten-carbonate fuel cell
MGO	marine gas oil
MTOE	million tons of oil equivalent
MUS$	million US dollars
NO_X	nitrogen oxides
NPV	net present value
OPEX	operating expenditure
OREDA	offshore and onshore reliability data
RBD	reliability block diagram
RISKEX	risk expenditure
SO_X	sulfur oxides

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