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Economic analysis of a zero-carbon liquefied hydrogen tanker ship

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HIGHLIGHTS

- Economic analysis of a novel liquified hydrogen tanker to achieve a zero-carbon target.
- Three scenarios been Investigated to achieve the economic feasibility of the LH2 carrier ship.
- Implementation of the LH2 carrier ship can cover the capital costs within 2.5 years.
- The Economic Added Value for the LH2 tankers can achieve $USD 213, 514, 868.00

ARTICLE INFO

Article history:
Received 9 May 2022
Received in revised form
16 June 2022
Accepted 18 June 2022
Available online 10 July 2022

Keywords:
Liquefied hydrogen
LH2 tanker
Hydrogen economy
Economic
Green economy
Tanker ship

ABSTRACT

The green hydrogen economy is considered one of the sustainable solutions to mitigate climate change. This study provides an economic analysis of a novel liquified hydrogen (LH2) tanker fuelled by hydrogen with a total capacity of ~280,000 m^3 of liquified hydrogen named 'JAMILA'. An established economic method was applied to investigate the economic feasibility of the JAMILA ship as a contribution to the future zero-emission target. The systematic economic evaluation determined the net present value of the LH2 tanker, internal rate of return, payback period, and economic value added to support and encourage shipyards and the industrial sector in general. The results indicate that the implementation of the LH2 tanker ship can cover the capital cost of the ship within no more than 2.5 years, which represents 8.3% of the assumed 30-year operational life cycle of the project in the best maritime shipping prices conditions and 6 years in the worst-case shipping marine economic conditions. Therefore, the assessment of the economic results shows that the LH2 tankers may be a worthwhile contribution to the green hydrogen economy.

Introduction

On October 31, 2021, the United Kingdom government hosted the 2021 United Nations Climate Change Conference (COP26) in Glasgow under the United Nations Framework Convention on Climate Change (UNFCCC) to implement the aim of the 2015 Paris Agreement to limit the global temperature increase to below 2.0 °C and to continuing the efforts to limit temperature increases to 1.5 °C [1]. To achieve these aims, there is a need to find an alternative to fossil fuels, which contribute

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https://doi.org/10.1016/j.ijhydene.2022.06.168

greatly to CO_2 emissions. Green hydrogen can potentially be used as an alternative decarbonisation fuel for transportation, industrial, and power generation sectors as a solution to achieve a zero-emissions by 2050 and reach climate change targets [2]. Moreover, there is a global interest into hydrogen utilisation as an alternative to traditional fuel; for example, currently, annual hydrogen consumption in the European Union (EU) is approximately 9.7 million tonnes (Mt) and is expected to increase; the EU has the potential to generate approximately 2250 TW per hour (TWh) of hydrogen by 2050 [3,4]. Currently, International Energy Agency (IEA) indicators show that yearly global hydrogen production is 120 Mt, representing approximately 4% of the final consumption of international energy and other sectors [5,6]. Economically, the current cost of green hydrogen is approximately USD$6/kg, which is considered a high cost due to the green hydrogen production costly electrolysis method using renewable energy sources (RES) [7,8]. However, by 2040, the cost is expected to decrease to USD$2/kg due to a reduction in green hydrogen production prices and an increase in the number of countries exporting hydrogen [9,10].

Several countries have shown tremendous interest in the investment in hydrogen technologies and utilisation; for example, in 2019, the Australian government committed to contributing approximately AUD$500 million to subsidise clean hydrogen projects in different sectors according to the Australian national hydrogen strategy. In addition, the Australian government has declared an investment package of AUD$70.2 billion for the activation of regional hydrogen export hubs [11]. Moreover, Canada supplies around 5% of global hydrogen production markets, approximately more than 3.5 Mt per year and this capacity is expected to be 20 Mt by 2050, which will cover 30% of Canadas end-use energy [12,13]. Additionally, the “Green Flamingo” project expected an investment of EUR$57 billion by installing 1 GW of electrolysis capacity to produce the green hydrogen and export it from the Port of Sines in Portugal to the Port of Rotterdam in the Netherlands [14,15]. Chile has a commitment strategy to green hydrogen production and exports using some of the best renewable sources in the world. The Chile green hydrogen project expects to achieve 25 GW of electrolysis by 2030 and export USD$2.5 billion/year of green hydrogen and derivatives [16]. Moreover, Neom planned to create a large project to produce >600 tonnes of hydrogen daily by 2025, and to utilise green hydrogen as an environmentally friendly energy source to achieve a sustainable hydrogen economy in the future [17]. However, this tremendous demand for hydrogen is expected to require hydrogen to be transported by liquified hydrogen carrier ships. In this regard, there is a need to construct more than 500 large-scale hydrogen tankers to manage global hydrogen supply and demand [2]; hydrogen may be an economically efficient option based on the high demand and global supply.

Understanding the economic criteria of hydrogen carrier ships is essential as one of the promising options for large-scale transport of green liquid hydrogen in the future. These aspects were analysed in the current study, which involved a high-level economic analysis of a large-scale liquified hydrogen tanker with a total capacity of 20,000 tonnes of liquified hydrogen. Previous related research focuses on the economic and design evaluation of large-scale liquified hydrogen carrier ships as an economical solution to shipping hydrogen overseas. In 1998, Abe et al. published an initial study of a preliminary design for a large-scale liquified hydrogen carrier ship with a total capacity of 200,000 m^3 and a total cargo weight of 14,000 tonnes of liquified hydrogen; however, this study did not include an economic analysis for the large-scale liquified hydrogen carrier ship, which is essential to polarise the hydrogen investors companies [18]. In 2020, Boretti [19] investigated the hydrogen production likeliness from the excess renewable energy for export this hydrogen from Australia to overseas. The results indicated that Australia is challenging to produce and export hydrogen by excess wind and solar energy through electrolysis in the future. It will be more beneficial for Australia to develop its use of natural gas as a useable source for electricity generation [19]. However, the study only focused on the hydrogen production stage and did not consider the economic analysis of the hydrogen transportation technology as an energy carrier, which is considered a critical factor in the hydrogen exportation supply chain [19]. In 2020, Ishimoto et al. [20] evaluated the value chains of hydrogen transportation from Norway to markets in Europe and Japan using liquified hydrogen and ammonia in terms of energy efficiency, environment, and cost of the different value chains. The economic aspect outcome showed that the liquification process and the difference in transportation distance play a key role in the total cost level of hydrogen [20]. In 2021, Okunlola et al. [21] evaluated the cost to deliver gaseous hydrogen and export it from Canada to Asia, Europe, and North America. The delivery cost to those overseas destinations was evaluated using techno-economic analysis. The evaluation covered five supply chain stages: Hydrogen production from steam methane reforming incorporated with 52% carbon capture, a long-distance inland hydrogen pipeline, hydrogen liquefaction, shipping, and regasification. The results showed that the supply chain costs of hydrogen for inland destinations in North America, Asia-Pacific, and Europe would be no more than CAD$6.03/kg, CAD$6.99/kg, and CAD$8.14/kg, respectively [21]. In 2022, Johnston et al. [22] developed an open-source model to assess the shipping cost of different hydrogen carrier forms over different journeys to support the hydrogen suppliers and consumers. The assessment includes the transportation of liquid hydrogen (LH2), ammonia, liquefied natural gas (LNG), methanol and liquid organic hydrogen carriers (LOHCs). According to the study, the implementation of the evaluation took into account the port fees, possible canal usage charges, fuel costs, ship capital and operating costs, boil-off losses and possible environmental taxes. The results indicated that for Australia to Rotterdam and Australia to Tokyo journeys presented the same merit order of hydrogen carriers, with the cost reduction owing to shorter transportation distance. The results indicated that ammonia is the cheapest hydrogen carrier, followed by methanol, LNG and LOHCs, and LH2 as more expensive than other hydrogen carrier forms. In addition, Ingason et al. [23] developed an optimisation model to offer an optimal solution to achieve the most economical way for hydrogen production and transportation from Iceland to continental Europe. Heuser et al. [24] applied a techno-economic analysis method to investigate the cost of the green hydrogen supply chain produced from wind-powered-electrolysis between Patagonia and Japan. Wijayanta et al. [25] contrasted and assessed three different hydrogen carriers (liquefied hydrogen (LH2), methylcyclohexane (MCH), and ammonia (NH3)) by conducting a long-term cost prediction analysis. The results indicated that the ammonia with direct utilisation had been considered to have the highest feasibility for massive adoption. If pure hydrogen is required as the end-use product, liquified hydrogen (LH2) could be a promising option as a carrier in the long run compared with other options. Brändle et al. [26] estimated the development of global production and supply costs of low carbon hydrogen from renewable energy sources and natural gas until the long term 2050. The analysis also evaluates the cost linked with the transportation of hydrogen using hydrogen carrier ships or pipelines. The results indicated that the green hydrogen produced from renewable energy sources could become an acceptable economic option in the coming years. By the long term 2050, the production costs for hydrogen from renewable energy sources could decrease to $1.5/kg as a minimum production cost. Furthermore, owing to the high cost of seaborne transport using hydrogen carrier ships, the hydrogen pipeline networks could be the future solution to develop the hydrogen trade globally.

From previous studies, it is evident that there is a high potential for seaborn shipping as an effective method to export and import hydrogen between production and consumption countries due to the predicted high future demand for hydrogen. Therefore, there is a need to understand the economic feasibility of future large-scale liquified hydrogen tankers to accelerate the use of hydrogen to achieve climate change commitments. However, to the best of the authors' knowledge, the economic feasibility assessment of a large-scale liquefied hydrogen carrier ship fuelled by hydrogen has not been considered yet. Thus, the novel contribution of this research is to determine the complexity and quality of the economic aspects of a large-scale liquified hydrogen carrier ship as a viable option to support international governments and ship manufacturers to take action regarding the hydrogen economy. Therefore, this study's objective was to conduct an economic assessment of a large-scale liquified hydrogen carrier ship with a total capacity of 280,000 m^3. In addition, the study addresses gaps in economic viability assessment in the long and short term for an actual-life use of the LH2 carrier ship as a major technology to contribute to the hydrogen economy supply chain.

Methodology

The following section describes the LH2 tanker ship economic assessment method based on established comprehensive economic analysis models [27]. The authors extended and developed these models to analyse the economics of LH2 tanker ships with a total capacity of ~280,000 m^3 as a promising future solution project to achieve a zero-emission target [2]. In this study, the authors assumed three scenarios for the liquified hydrogen carrier ship economic estimation. In the first scenario, 'short-term 2020', the hydrogen price is USD$6/kg [7,8] and the hydrogen shipping price is USD$1.2/kg [28]. The second scenario is 'long-term 2040', wherein the fuel price will decrease to USD$2/kg [9] and the shipping cost will be the same as that in the short-term 2020 scenario. Finally, the third scenario, 'long-term 2050', assumes that the hydrogen cost is USD$2/kg [9] and that the cargo shipping cost will decrease to USD$0.7/kg from 2050 onwards due to the proliferation of hydrogen tanker ships which creates prices competition for hydrogen shipping.

Economic evaluation strategy

This study used a Business Model Canvas (BMC) as an effective strategic management tool to economically communicate, economically define, and assess the monetary costs and benefits of the LH2 tanker ship as a future promising green project. Table 1 shows the fundamental elements of the BMC used to estimate the economic feasibility of the LH2 carrier ship. In addition, the BMC describes capital, annual, emission, and investment costs, as these costs are considered essential to the economic analyses and envisioning future profits for the LH2 tanker ship project.

Essential costs description

The capital cost is defined as a one-time cost to start the business. The capital cost in this study was calculated based on: The weight of the ship hull, engine output power, and the number of Azimuthal pods as a part of propulsion system; and hydrogen cargo, fuel tanks, and ship machinery costs as major elements for the LH2 tanker ship. However, the total capital cost in this study was assumed to be a constant cost for short and long-term scenarios due to the expectation of no change in primary component materials of the ship through the 30-year operational period.

The second cost is the annual cost: The yearly income of the project was estimated based on inflow and outflow costs calculations. In this study, the LH2 tanker ship inflow was confined to the cargo shipping cost, excluding the boil-off rate, which is 200 tons for each 20-day return journey [2]. Therefore, the variation in the shipping cost in each scenario will be the leading indicator to calculate the yearly income of the LH2 tanker ship. The outflow for the LH2 tanker ship project depends on fuel, boil-off from cargo tanks, emission taxes, and operation and maintenance costs. The main factor in the outflow cost is the variation in the hydrogen price, which will determine the fuel cost, and this cost is expected to decrease in the long term [9]. The crew cost was accounted for to estimate the total absolute annual income from the LH2 tanker ship.

The third cost is emission cost: Green hydrogen has been considered one of the leading solutions to achieve the maritime zero-emission target [29]; for this reason, the authors assumed that there are no emission taxes and penalties charged to the green hydrogen used in this study.

The fourth cost is an investment, i.e., the supplementary cost required to set up and run the project. In this study, this cost was employed to design, research, and develop the tanks and hull materials, and for manufacturing, engineering and supervision, consulting, contingency, and science and technology. The investment cost was calculated as an initial cost for the project, and

Table 1 – Business model canvas for LH2 tanker ship.

Capital cost	Annual cost	Emission Cost	Economic analysis
☐ LH2 cargo tanks	☐ Inflow	☐ NOx	☐ Payback period
■ Tanks materials	■ Cargo shipping		☐ Net present value
■ Isolated materials.			☐ Internal rate of return
■ Tank structures.			☐ Profitability index
■ LH2 pipeline			☐ Economic added value
■ LH2 tanks accessories and equipment's			
☐ Hull construction	☐ Outflow		
■ Materials	■ Maintenance		
■ Super structure	■ Operation		
☐ COCAS	■ Fuel cost		
■ Gas turbine LM2500+	■ Boil off from cargo tank		
■ Single pressure HRSG	■ Emission tax		
■ Steam turbine			
■ Condenser			
■ Pump			
■ Electric generators			
☐ Azimuthal pods			
■ Four blades propeller			
■ Electric cables			
■ Electric Motors			
■ System equipment's			
☐ Ship machinery and systems			
Investments cost		Revenue	
☐ Manufacturing costs		☐ Operation distance	
☐ Engineering and supervision		☐ Fuel cost	
☐ Consulting and contingency		☐ Cargo Boil off	
☐ Science and technology		☐ Maintenance cost	
☐ Research and development		☐ Emission cost	

this cost can be used for more than one version of the project because the same process will apply to all the versions from the same project. The authors assumed this cost would cover approximately 20 LH2 tanker ships in this study.

Economic analysis explanation

BMC involves four effective tools to assess the LH2 tanker ship toward ensuring the economic feasibility of the project. Those tools represent the central key role of the economic analysis for short and long-terms scenarios. The leading four tools are as follow.

- Net present value (NPV) is one of the primary metrics in finance in the industrial sector and is applied to the cash flow of a project to evaluate the current and future industrial investment projects [27,30]. Therefore, a low NPV signifies a critical financing indicator to the enterprise, ensuring project loss and vice versa. Furthermore, economically, a negative NPV leads the investor to reject the project, especially when the NPV value is lower than the project initial investment amount; conversely, the investor will accept the positive NPV when the NPV is higher than the initial investment outlay [27]. Therefore, this research applied the NPV for LH2 tanker ships as a promising project through three scenarios. Furthermore, for increased accuracy, the authors examined the influence of the discount rate for the NPV value; this rate was be assumed to be constant at 4% for each scenario through 30 years as a project operation life cycle [30]. Therefore, as a critical metric for this project, the NPV can be calculated using Equation (1) [31], where X_t is the future net cash flows, R is the average periodic rate to invest, and t, n is a time.

$$NPV = \sum_{t=0}^{n} \frac{X_t}{(1+R)^t} \tag{1}$$

- Internal rate of return (IRR) is a method used to evaluate the project capability to achieve investor trust, and is defined as the stage when the project NPV equals zero. The criterion for acceptance of the project depends on the IRR percentage relative to the discount rate; if the IRR percentage is higher than the discount rate, the investor will accept the project and the investment is considered profitable. This method was applied in this study over 30 years for each scenario for the LH2 tanker ship to estimate the different IRR percentages. In addition, the estimation included the extended internal rate of return (XIRR) by using specific dates to obtain the estimation accuracy. Equation (2) was applied to calculate the IIR [32], where C_t is the future cash flow, IRR is the internal rate of return, and t, n is the total period.

$$\sum_{t=0}^{n}\frac{C_t}{(1+IRR)^t}=0 \quad (2)$$

- The payback period (PP) is the tool representing the required operational period of the project to cover the initial business investment. The criteria to evaluate the project using this tool are established as follows: A low PP indicates that the investor will accept the business due to the high-profit achievability; conversely, a high PP means that the project is non-profitable [27]. In this study, the PP depended on the total yearly absolute income from carrying liquified hydrogen and the influence in the hydrogen shipping prices in the long term. Equation (3) was applied to calculate the PP, where I_o is the initial investment and C_a is the net annual cash inflow [27].

$$PP=\frac{I_o}{C_a} \quad (3)$$

- Economic value added (EVA) is a method used to calculate the economic profit of projects in large-scale business sectors. A project with a high EVA is usually more efficient than one with a lower EVA. In addition, this tool can compare the efficiency of more than one project to differentiate between projects in the event of multiple investment options [33–35]. This tool is effective for the LH2 tanker ship due to the differences in the hydrogen and shipping prices over 30 years. This method was applied for each scenario with a 10-year period, changing the percentage of the weighted average cost of capital (WACC) for each scenario to determine the period of the highest EVA value. Equation (4) was used to estimate the EVA, where *NOPAT* is the net operating profits after tax and *WACC* is the weighted average capital cost.

$$EVA=NOPAT-(WACC\times Capital\ investment) \quad (4)$$

Case study

The authors collected the JAMILA hydrogen carrier ship data from authentic published sources [2] to create the economic assumptions for the hydrogen carrier ship as follows:

1. The cost of liquified hydrogen cargo and boil-off per tonne is USD$6/kg based on the European Commission July 2020 hydrogen strategy [7] for the short-term scenario and USD$2/kg for long-term 2040 and 2050 scenarios [9], whereby the cargo is assumed to be green hydrogen. The total cargo weight includes 0.1% of boil-off, i.e., 20,000 tonnes, which will have cost a USD$120, 000, 000/voyage for the short-term scenario and USD$40, 000, 000/voyage for long-term scenarios. Furthermore, the authors assumed that the ship was designed with an average speed of 18 knots to operate for 20 days as a maximum period for a return journey based on a previous study [2], equating to 12 journeys per year; in this case, the cargo will have a total cost of USD$1,440, 000, 000/year in the short-term and USD$480, 000, 000/year in the long-term, including boil-off, as a total yearly cargo price.
2. 30-years lifetime operational hours for the JAMILA ship have been appointed until its retirement.
3. Based on a previous study [36], the crew cost is USD$1,460,000/year established on the Very Large Crude Carrier (VLCC) crew size.
4. The authors assumed that the income cash flow is constant for the entire 30-year operation of the JAMILA ship.
5. The emission taxes and charges were neglected in this study due to the low NO_x emission produced by the hydrogen carrier ship [37].
6. The ship was designed to consume around 2.87 t/h of green hydrogen fuel, which costs USD$17220/hour for a short-term scenario. This cost includes 0.1% of boil-off, representing 0.83 t/h from the cargo tanks. Therefore, the total fuel consumption is assumed to be 16531.2

Table 2 – Estimated LH2 carrier ship capital cost.

JAMILA LH2 carrier ship capital cost			
Item	Cost	Unit number	Total cost (USD$)
Ship hull and super structure construction	3.49 USD$/kg [39]	51,334,000 kg [2]	179,155,660.00
Combined cycle gas turbine (COGAS)	26,500,000 USD$ [42]	50 MW–LM2500 GOGAS [2,38]	26,500,000.00
Azimuthal pods electrical propulsion system	15,000,000 USD$ [43]	15.5 MW each of two azimuthal-podded propellers [38]	30,000,000.00
Ship machinery and equipment's	15USD$/m^{3}of LBT [39]	LBT is 277,500 m^3 [2]	4,162,500.00
LH2 cargo and engine fuel tanks (long-term falling $200,000,000 per ship) based on: • Wall material (Aluminium 4.4% Cu) • Insulation foam (Rigid closed-cell Polyurethane) • Liner alloy (Aluminium 5086) • Construction outlay • LH2 storage system and equipment	30 USD$/kg [40,41]	20,000,000 kg [2]	200,000,000.00
Total capital cost			439,818,160.00
Investment cost (for a class of 20 ships)	41 USD$/kg [40]		41,000,000.00 (for each ship)
Total			**480,818,160.00**

Table 3 – Estimated LH2 carrier ship cash inflow and outflow.

JAMILA LH2 carrier ship cash flow estimated for 20-day return journey				Units
Inflow	Short term (2020)	Long term (2040)	Long term (2050)	–
Cargo shipping (19,800 tonnes) [2]	1.2 [28]	1.2 [28]	0.7	USD$/kg
Total inflow	**23,760,000**	**23,760,000**	**13,860,000**	**USD$/Journey**
Outflow	**Short term (2020)**	**Long term (2040 and 2050)**		-
Fuel (1377.6 tonnes–200 tonnes boil off) [2]	6 [7] (– 7,065,600)	2 [9] (– 2,355,200)		USD$/kg (USD$/Journey)
Operation and Maintenance (20,000 tonnes) [2]	1.7 [44] (– 2,800,000)	1.7 [44] (– 2,800,000)		USD$/kg per year (USD$/Journey)
Boil off from cargo tank (200 tonnes) [2]	6 [7] (– 1,200,000)	2 [9] (– 400,000)		USD$/kg (USD$/Journey)
Emission tax	0	0		USD$/Journey
Total outflow	**– 11,065,600**	**– 5,555,200**		**USD$/Journey**
Period	**Short term (2020)**	**Long term (2040)**	**Long term (2050)**	-
Total income	**12,694,400**	**18,204,800**	**8,304,800**	**USD$/Journey**
Yearly income (12 journeys/year)	152,332,800	218,457,600	99,657,600	USD$/year
Crew cost	– 1,460,000	– 1,460,000	– 1,460,000	USD$/year
Absolute total yearly income	**150,872,800**	**216,997,600**	**98,197,600**	**USD$/year**
Absolute 30-year income	**4,526,184,000**	**6,509,928,000**	**2,945,928,000**	**USD$**

tonnes/year, with a fuel cost of USD$99, 187, 200/year [38]. For the long-term period, the ship fuel cost will be USD$5740/hour, including the boil-off from the cargo tanks; consequently, in this case, the total fuel cost per year is assumed to be USD$33, 062, 400/year [38].

7. Some data was calculated based on the liquefied natural gas (LNG) carrier ships due to the global limitations in hydrogen carrier ship designs [39].
8. The cost of LH2 cargo and prime mover fuel tanks is assumed to be USD$30/kg [40,41], which is a total cost of USD$600, 000, 000 based on hydrogen carrier ship design [2,40]. This amount is assumed to decrease in the long-term period and is estimated to be USD$200, 000, 000/ship.
9. The investment cost for design, research, and development of the tanks and hull materials, manufacturing, engineering and supervision, consulting, and contingency, science and technology is estimated to be USD$41/kg [40], which equates to USD$820, 000, 000.00 as a total investment cost (assumed for a class of 20 ships).
10. The cargo shipping cost is assumed to be USD$1.2/kg for the short-term 2020 and long-term 2040 scenarios [28], and the authors assumed that the cargo transportation price would decrease to USD$0.7/kg in 2050.

Results and discussion

The economic assessment results and cost details for the JAMILA LH2 tanker ship are presented in this section based on the BMC, shown in Table 1. In terms of the capital cost of the JAMILA LH2 tanker ship, which is presented in Table 2, the results show that the LH2 cargo and engine fuel tank costs have the most significant effect on the LH2 tanker ship capital cost due to the liquified hydrogen tanks specifications, such as high insulation requirements and high material weights compared with the conventional liquid cargo tanks. It is assumed that this cost will decrease in the long-term period, which will positively affect the economic efficiency of the ship in the future. However, LH2 cargo and engine fuel tank costs need to be considered in the stages of developing, manufacturing, and material cost calculations. Moreover, the ship hull cost is classified as the second-highest cost that falls under the capital cost estimation due to the increase in the hull weight, which is 51,334 tonnes, compared with the conventional tanker ships in similar dimensions of the LH2 tanker ship. This high weight helps to achieve ship stability requirements and increases the hull efficiency to safely carry the liquified hydrogen tanks. This analysis revealed that the total capital cost of an LH2 tanker ship with 20,000 tonnes of

Table 4 – JAMILA ship net present value (NPV).

NPV	Short term (2020)	Long term (2040)	Long term (2050)	Units
Discount rate	4.0 [30]	4.0 [30]	4.0 [30]	%
Number of years	1–30	1–30	1–30	Year
Discount factor	0.96–0.31	0.96–0.31	0.96–0.31	%
Undiscounted cash flow	$150,872,800	$216,997,600	$98,197,600	$USD/year
Present value	$145,070,000–	$208,651,538–	$94,420,769–	$USD/year
NPV	$46,516,901	$66,904,411	$30,276,153	$USD
Value of the discount	**$2,608,897,482**	**$3,752,329,725**	**$1,698,036,169**	$USD/year
	$5,802,800–	$8,346,062–	$3,776,831–	
	$104,355,899	$150,093,189	$67,921,447	

liquified hydrogen capacity is approximately USD$480, 818, 160, which is acceptable compared to that of a LNG carrier ship of a similar size.

The next part of the economic evaluation involved a cash flow estimation for the JAMILA ship. The results showed that the difference in the liquified hydrogen price does not affect the LH2 ship total inflow. However, economically, it was observed from the cash flow results that the shipping cost plays a significant role in the inflow estimation. Table 3 shows the negative effect in the inflow in the long-term 2050 scenario due to decreased shipping cost; this effect decreased the inflow value from USD$23, 760, 000/journey to USD$13, 860, 000/journey for 19,800 tonnes of liquified hydrogen as a whole load cargo (excluding 200 tonnes boil off) for a 20-day return journey.

Moreover, the outflow estimation for the same scenarios was calculated based on fuel cost, boil-off from cargo tanks, and operation and maintenance costs. In this case, the liquified hydrogen price will significantly affect the outflow amount of the LH2 tanker ship. Table 3 shows that the total outflow cost in the long-term 2040 and 2050 scenarios is less than half the cost in the short-term 2020 scenario, due to the reduction in the liquified hydrogen price by 2040, which has a positive effect on total outflow due to the decrease in the costs of fuel and the liquified hydrogen boil-off from the tanks in case of the long-term 2040 and 2050 scenarios. Additionally, Table 3 shows that the total 30-year income for 12 journeys/year in the long term 2040 scenario is USD$6,509, 928, 000, which is higher than that of the short-term 2020 and long-term 2050 scenarios. This due to the hydrogen price, which is USD$2/kg compared with USD$6/kg in the short-term 2020 scenario, and the hydrogen shipping cost which is USD$1.2/kg compared with USD$0.7/kg in the long-term 2050 scenario. Therefore, based on the cash flow results, to achieve the optimum income from the LH2 tanker ship, there is a need to lower hydrogen prices and maintain shipping costs.

The cash flow results is one of the keys to estimating the NPV for the JAMILA LH2 tanker ship. Table 4 shows the NPV calculations for each scenario to estimate the amount of profitability realised by investing in the JAMILA ship for 30 years. The authors assumed that the discounted rate for each scenario was 0.4% [30], and the range of the discount factors for a 30-year period is from 0.96% over the first year to 0.31% for the last year. The results indicated that in the long-term 2050 scenario with a discounted value of 4%, the lowest NPV with the amount of USD$1,698, 036, 169 is acceptable compared with the other scenarios. Therefore, this NPV gain from the large scale LH2 tanker ship project shows that the investment is acceptable. The long-term 2040 scenario achieved the highest present value of USD$3,752, 329, 725 with the same discounted value; however, this achievement is due to the high yearly income cash flow.

The IRR for the LH2 tanker ship was employed to assess the potential profitability of the investment. Then, the IRR was applied to determine the precise discounted percentage needed for the cash flow of the project to realise a NPV of zero. Table 5 presents the IRR percentages of the LH2 tanker ship for 30 years (as the estimated lifetime of a ship) for the evaluated scenarios. The results showed that the highest IRR is 45.13% in the long-term 2040 scenario (compared to 20.25% in the worst-case scenario, i.e., the long-term 2050 scenario). The IRR percentage for the worst-case scenario can achieve the high potential of low-risk investment. This IRR of the project achieved a very high and unusual percentage; this achievement is due to the yearly income of the project being very high compared with the total capital cost of the project.

The authors estimated the XIRR for the LH2 carrier ship using specific dates to obtain precise calculations. Table 6 shows the IRR from June 28, 2025 to December 30, 2053 for each year in short and long-term scenarios. The results showed that the XIRR for the LH2 carrier ship in the long-term 2040 scenario is 56.26%; conversely, in the long-term 2050 scenario, the percentage is 22.50% which offers an acceptable value for investors to maintain the successful operation of the project.

To estimate the period needed for the cost of the project investment to be covered, we applied the PP assessment method. Table 7a–c shows the PP for LH2 tanker ship investment from years 0–30. The short-term 2020 scenario does not need more than 3.5 years to cover the LH2 tanker investment. In the case of the long-term 2040 scenario, the PP is not more than 2.5 years, representing a short period compared with that of other projects due to the high NPV and the IRR. However, this is profitable, considering that less than 2.5 years of the project running life cycle represents 8.3% of the assumed 30-year operation of the LH2 tanker ship. Finally, in the long-term 2050 scenario, the results inTable 7c show that the PP is approximately 6 years, representing 20% of the projects operational period; however, it is still acceptable compared with other investments.

From a financial performance perspective, the economic evaluation of the LH2 tanker ship sustainability was based on

Table 5 – JAMILA ship internal rate of return (IRR).

Period		1–30 years	Short term (2020)		Units
IRR	31.37%	Year 1 −480,818,160.0	Each year 150,872,800	Year 30 150,872,800	Year $USD/year
Period		**1–30 years**	**Long term (2040)**		**Units**
IRR	45.13%	Year 1 −480,818,160.0	Each year 216,997,600	Year 30 216,997,600	Year $USD/year
Period		**1–30 years**	**Long term (2050)**		**Units**
IRR	20.25%	Year 1 −480,818,160.0	Each year 98,197,600	Year 30 98,197,600	Year $USD/year

Table 6 – JAMILA ship extended internal rate of return (XIRR).

Period		1–30 years	Short-term (2020)		Units
XIRR	36.59%	28/06/2025 −480,818,160.0	Each year 150,872,800	30/12/2053 150,872,800	Year $USD/year
Period		1–30 years	**Long-term (2040)**		**Units**
XIRR	56.26%	28/06/2025 −480,818,160.0	Each year 216,997,600	30/12/2053 216,997,600	Year $USD/year
Period		1–30 years	**Long-term (2050)**		**Units**
XIRR	22.50%	28/06/2025 −480,818,160.0	Each year 98,197,600	30/12/2053 98,197,600	Year $USD/year

Table 7a – JAMILA ship payback period (PP).

PP	Short term (2020)			Units
Investment	Year 0	Each year	Year 30	Year
Cash flows	$480,818,160.0	$150,872,800	$150,872,800	$USD/year
PP = $480,818,160.0/$150,872,800 = 39 Months				

Table 7b – JAMILA ship payback period.

PP	Long term (2040)			Units
Investment	Year 0	Each year	Year 30	Year
Cash flows	$480,818,160.0	$216,997,600	$216,997,600	$USD/year
PP = $480,818,160.0/$216,997,600 = 27 Months				

Table 7c – JAMILA ship payback period.

PP	Long term (2050)			Units
Investment	Year 0	Each year	Year 30	Year
Cash flows	$480,818,160.0	$98,197,600	$98,197,600	$USD/year
PP = $480,818,160.0/$98,197,600 = 59 Months				

the EVA. This method indicates the economic value contribution of the LH2 tanker ship for the future. Therefore, it is essential to establish the investment cost per year that is expected to apply EVA and sustain the LH2 tanker ship project. Table 8 shows the investment cost required for the project per year, including fuel, crew, maintenance, and operation costs.

Table 8 – JAMILA ship investment cost.

Investment cost	Short term (2020)	Long term (2040 and 2050)	Units
Fuel cost	84,787,200 [2,7]	28,262,400 [2,9]	$USD/year
Crew cost	1,460,000 [36]	1,460,000 [36]	$USD/year
Operation and maintenance costs	33,600,000 [44]	33,600,000 [44]	$USD/year
Total cost	119,847,200	63,322,400	$USD/year

Table 9 – JAMILA ship economic value added (EAV).

Economic value added estimation (Short term 2020)			
Year	2020	2021–2025	2025–2030
Capital invested (beginning of year) $USD	600,665,360	119,847,200	119,847,200
Weighted average cost of capital (WACC) %	5	5.5	6
Finance charge $USD	**30,033,268.00**	**6,591,596.00**	**7,190,832.00**
Net operating profit after tax $USD	150,872,800	150,872,800	150,872,800
Economic value added $USD	**120,839,532.00**	**144,281,204.00**	**143,681,968.00**
Economic value added estimation (long-term 2040)			
Year	**2040**	**2041–2045**	**2045–2050**
Capital invested (beginning of year) $USD	544,140,560	63,322,400	63,322,400
Weighted average cost of capital (WACC) %	5	5.5	6
Finance charge $USD	**27,207,028.00**	**3,482,732.00**	**3,799,344.00**
Net operating profit after tax $USD	216,997,600	216,997,600	216,997,600
Economic value added $USD	**189,790,572.00**	**213,514,868.00**	**213,198,256.00**
Economic value added estimation (long-term 2050)			
Year	2050	2051–2055	2055–2060
Capital invested (beginning of year) $USD	544,140,560	63,322,400	63,322,400
Weighted average cost of capital (WACC) %	5	5.5	6
Finance charge $USD	**27,207,028.00**	**3,482,732.00**	**3,799,344.00**
Net operating profit after tax $USD	98,197,600	98,197,600	98,197,600
Economic value added $USD	**70,990,572.00**	**94,714,868.00**	**94,398,256.00**

It is noticeable that the fuel cost is the primary factor in the investment cost estimation for LH2 tanker ships. Table 8 shows that the total investment cost for the project in the short-term 2020 scenario is USD$119, 847, 200/year, which is higher than that for the long-term 2040 and 2050 scenarios (USD$63, 322, 400/year). The variation of hydrogen price is the main reason for the difference in total investment cost for each scenario. The following assumptions were made to support the EAV estimation:

- The tax rate on LH2 shipping using tanker ships as income is zero.
- The WACC assumed based on calculation to be 5–6% with a percentage of 0.5 as an annual increase [45].
- The net operating profits after tax (NOPAT) are assumed as follows:
  - NOPAT for short-term 2020 = USD$150, 872, 800.
  - NOPAT for long-term 2040 = USD$216, 997, 600.
  - NOPAT for long-term 2050 = USD$98, 197, 600

Table 9 shows that the highest EVA values for the short-term 2020, long-term 2040, and long-term 2050 scenarios are USD$144, 281, 204.00, USD$213, 514, 868.00, and USD$94, 714, 868.00, respectively. The differences in EVA in each scenario are based on the finance charged values, as shown in Table 9. However, the EVA results confirmed that the LH2 tanker ship will be a promising and sustainable project in the future.

Conclusions

An established economic method was applied to assess the economic benefits for the LH2 tanker ship with a total capacity of 280,000 m^3 as a future solution to contribute to achieving the global commitments to mitigate climate change. The economic feasibility was analysed using comprehensive economic models through three scenarios for the liquified hydrogen carrier ship. In the first scenario, short-term 2020, the hydrogen price was USD$6 and the hydrogen shipping price was USD$1.2/kg. The second scenario, long-term 2040, assumed that the fuel price will decrease to USD$2/kg and the shipping cost will be the same as in the short-term 2020 scenario. Ultimately, the third scenario, long-term 2050, assumed that the hydrogen cost is USD$2/kg, and that the cargo shipping cost will decrease to USD$0.7/kg from 2050. The results were found to be promising for the hydrogen economy. The key results are summarised as follows:

- The total capital cost of an LH2 tanker ship with 280,000 m^3 of liquified hydrogen capacity was estimated to be approximately USD$480, 818, 160; this represents an acceptable cost compared with the absolute total yearly income in each scenario.
- In the long-term 2050 scenario, the inflow value decreased by 58.3% compared with the short-term 2020 and long-term 2040 scenarios due to the liquified hydrogen shipping cost decreasing from USD$1.2 to USD$0.7/kg. Therefore, the shipping cost plays a significant role in the total yearly income value of the LH2 tanker ship.
- In the long-term scenarios, the outflow value decreased by 50.2% compared with that of the short-term 2020 scenario. This difference is due to the reduction in the liquified hydrogen price in the future, which caused a positive effect on the total yearly income value due to the decrease in fuel costs and the liquified hydrogen boil-off from the tanks.
- In the long-term 2040 scenario, the absolute 30-year income for 12 journeys/year achieved USD$6,509, 928, 000, which was higher than those of the short-term 2020 and long-term 2050 scenarios. This difference was due to the hydrogen price reduction, (i.e., USD$2/kg, compared with USD$6/kg in the short-term 2020 scenario) and the hydrogen shipping cost moderation (i.e., USD$1.2/kg, compared with USD$0.7/kg in the long-term 2050 scenario).
- In the long-term 2050 scenario, the NPV of USD$1,698, 036, 169 was lower than that of the other scenarios; this NPV gain from the large-scale LH2 tanker ship project indicated that the investment is acceptable. The long-term 2040 scenario reached the highest NPV of USD$3,752, 329, 725 with the same discount value of 4%; this achievement is due to the high yearly income cash flow.
- In the long-term 2040 scenario, the IRR was 45.13%, and in the worst-case scenario (i.e., the long-term 2050 scenario) the IRR was 20.25%; these percentages can achieve a promising low-risk investment. This project IRR achieved a very high and unusual percentage; this achievement is due to the very highly yearly income of the project compared with the project total capital cost.
- The PP for the LH2 tanker ship investment in the short-term 2020, long-term 2040, and long-term 2050 scenarios require no more than 3.5, 2.5, and 6 years, respectively, to cover the project investment, which represent 8.3%, 11.6%, and 20%, respectively, of the assumed 30-year operational period of the LH2 tanker. These periods are profitable compared to other projects, and for the same reason as mentioned above, the yearly income of the project is very high compared to the total capital cost of the project.
- The EVAs for the short-term 2020, long-term 2040, and long-term 2050 scenarios were USD$144, 281, 204.00, USD$213, 514, 868.00, and USD$94, 714, 868.00, respectively. The EVA results established that the LH2 tanker ship would be a promising and sustainable project in the future.

Credit author statement

Abdullah NFNR Alkhaledi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software. Suresh Sampath: Supervision. Pericles Pilidis: Supervision.

Declaration of competing interest

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

Acknowledgements

The authors are grateful to the Government of the State of Kuwait and the Public Authority for Applied Education and Training (PAAET) for provisions and financial support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2022.06.168.

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2022-07-10

Alkhaledi ANFNR, Sampath S, Pilidis P. (2022) Economic analysis of a zero-carbon liquefied hydrogen tanker ship, International Journal of Hydrogen Energy, Volume 47, Issue 66, August 2022, pp. 28213-28223

https://doi.org/10.1016/j.ijhydene.2022.06.168