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Comparative Analysis of Space-Based Battery, Fuel Cell, and Conventional Propulsion System for General Cargo Ships Of Approximately 100 Meters

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***Abstract*— this research aims to serve as a guidebook or framework for designing a general cargo ship, approximately 100 meters in length, by replacing the conventional diesel system with hydrogen and fuel cell technology. The reference vessel for this study is the general cargo ship with about 100m length operated in Baltic Sea. The results of this research provide the foundational calculations for designing a ship powered by hydrogen fuel cells, including the selection of hydrogen type, battery choice, and compliance with class standards. Additionally, the transformation of the ship's layout is a key outcome of this study. Based on the calculations, the ship, with a sailing duration of approximately three days, requires around 2800 kg of liquid hydrogen. This hydrogen supply can support 4 x 200 kW fuel cells and 5 x 70 kWh batteries. Ultimately, this allows for the design of a hydrogen-powered ship with an endurance of three days.**

Keywords—fuel cell, hydrogen, battery, ship, layout.

I. Introduction

The maritime industry has long relied on diesel engines for their robust power and reliability. However, the environmental toll of these engines is significant, as they emit harmful pollutants such as nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter. These emissions contribute considerably to air and water pollution, prompting global regxulatory bodies to impose stricter emission controls. As a result, the industry is increasingly exploring cleaner alternatives, with fuel cells emerging as a viable solution. this allows for the design of a hydrogen-powered ship with an endurance of three days

Fuel cells generate electricity through an electrochemical process involving hydrogen and oxygen, differing fundamentally from traditional combustion-based power generation. This process is notably efficient, as it avoids the substantial energy losses associated with heat and friction in conventional engines. Unlike diesel engines, fuel cells produce electricity with minimal emissions, aligning with global sustainability goals. The potential benefits include reduced fuel consumption, lower operating costs, and a significant reduction in greenhouse gas emissions.

However, integrating fuel cells into existing roro passenger ships presents unique challenges, particularly in terms of space constraints. Fuel cell systems require additional components, such as hydrogen storage tanks and auxiliary equipment, which occupy more space than traditional diesel engines. Moreover, the relatively slow ramp-up time of fuel cells necessitates the integration of batteries to manage peak power demands and rapid load changes.

This study focuses on the feasibility of replacing diesel engines with fuel cells on the motor vessel. It involves an in-depth analysis of the available space, potential layout configurations, and the technical challenges associated with such a conversion. By exploring these aspects, the research aims to contribute to the broader effort of reducing the maritime industry's environmental footprint and advancing sustainable ship propulsion technologies.

II. Method

A. Literature Review

A comprehensive review of existing literature, including journal papers, books, and industry reports, was conducted. This review focused on the use of hydrogen as a marine fuel, fuel cell technologies, and previous case studies on fuel cell integration in maritime applications. The goal was to understand the current state of technology and identify knowledge gaps.rite the complete author’s name without academic degrees for all of authors.

B. Problem Identification

Key challenges and constraints associated with integrating fuel cells into existing vessels were identified. These included issues related to space requirements, system compatibility, and operational limitations.

C. Data Collection

Relevant data was collected from various sources, including technical specifications of existing marine propulsion systems, fuel cell technologies, and hydrogen storage solutions. This data provided the foundation for subsequent analysis and modeling.

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D. BHP Engine Investigation

An investigation into the brake horsepower (BHP) requirements of the existing diesel engines on the MV was conducted. This step involved analyzing the vessel's power demands to determine the equivalent power output needed from a fuel cell system.

E. Selection of Fuel Cell

Based on the power requirements identified, suitable fuel cell systems were selected. Criteria for selection included efficiency, size, weight, and compatibility with maritime applications.

F. Fuel Consumption Estimation

An estimation of the hydrogen fuel consumption was performed, considering the vessel's operational profile and the efficiency of the selected fuel cells. This estimation was crucial for determining the size and number of hydrogen storage tanks required.

G. Modelling of Avaiable Space

A model was created to estimate the space available on the MV for the new propulsion system. This involved assessing the current layout and identifying areas where the fuel cell system, hydrogen tanks, and auxiliary equipment could be installed.

H. Selection of New Propulsion System Equipment

The necessary equipment for the new propulsion system, including the fuel cell stack, hydrogen storage tanks, and other components, was selected. This selection considered factors such as space constraints, weight distribution, and integration with existing systems.

I. Sizing Hydrogen Tanks

The hydrogen storage requirements were calculated, and the appropriate size and number of tanks were determined. This step ensured that the vessel could carry sufficient hydrogen for its intended range and operational profile.

J. Feasibility Analysis

A feasibility analysis was conducted to evaluate the practicality of the proposed fuel cell system. This analysis considered technical, economic, and regulatory aspects, including safety regulations and potential cost implications.

K. Designing Engine Room Layout

A new layout for the engine room was designed to accommodate the fuel cell system and associated equipment. This design aimed to optimize space utilization, ensure safe operation, and maintain ease of access for maintenance and inspection.

III. Results and Discussion

A. Eliminating Useless Equipments

The initial step is to analyze the current condition of the ship. In the process of transforming the diesel system to a hydrogen fuel cell system, different equipment will inevitably be used. Some equipment will become redundant in the hydrogen system. Therefore, we analyze what will be discarded so that we can reallocate that space for the needs of the hydrogen system.

TABLE 1.
LIST OF USELESS TANKS

Tank Name	Weight (ton)	Location
Fuel Oil	39.14	Machine Room
Fuel Oil Wing Tank	4.74	Wing (SB & PS)
Lubricating Oil	0.36	Machine Room
Bilge Holding Tank	2.18	Machine Room
Sludge Tank	2.49	Machine Room

Additionally, some equipment will be modified even though their functions remain the same. For example, the compressor. The ship will still need a compressor, but we can replace it with one of lower specifications because we no longer need starting air. This way, space can be optimized further.

TABLE 2
LIST OF USELESS EQUIPMENTS

Equipment	Total	Location
Fuel Transfer Pump	1	Machine Room
Fuel Separator Feed Pump	2	Machine Room
Fuel Circulating Pump Aux. Engine	2	Machine Room
Fuel Stand-by Pump	1	Machine Room
Lubricating Oil Stand-by Pump	1	Machine Room
Lubricating Oil Separator Unit	1	Machine Room
Oily Water Separator	1	Machine Room
Oily Bilge Pump	1	Machine Room
Compressor	2	Machine Room
Air Receiver	2	Machine Room

B. Power Calculation

First of all, the task is to convert the EHP requirements from the old machine to the new machine. This is done so that we can determine the load that needs to be supplied by the power source later. Using the derived Ship Transmission formula, here is the table of calculation results:

TABLE 3
SHIP DRIVE TRAIN AND POWER OF OLD PROPULSION SYSTEM

Ship Drive Train	Power (kW)
BHP	588.0
SHP	576.2
DHP	564.7
EHP	364.5

After the EHP of the old machine is known, we now convert it to the BHP of the new machine that will be designed with an electric motor. Here is the calculation and the conversion result:

TABLE 4
SHIP DRIVE TRAIN AND POWER OF NEW PROPULSION SYSTEM

Ship Drive Train	Power (kW)
BHP	624.9

Therefore, the new motor selected is:

TABLE 5
ELECTRIC MOTOR SPECIFICATION

Motor Selection		
Brand	Hoyer Motors	
Type	Y2E2 400L3-4	
Power	630	kW
Volt	400	V
Eff	96.20%	
RPM	1490	

C. LH2 Requirement and Tank

To calculate the hydrogen requirements, we first need the following data:

TABLE 6
OPERATION SPECIFICATION

Maximum endurance	3.26	days	Data collected from the longest sailing route from Klaipeda – Husum
Engine Power	630	kW	Ship Specification
Others Load	30	kW	Ship Specification

The power for each sailing condition is determined using percentage assumptions derived from calculations of existing ships. Below is a table showing the power calculations for each sailing condition:

TABLE 7
POWER CALCULATION

Condition	Formula	Power (kW)
Sailing	Engine Power + Hotel Power	660
Manoeuvring	110% x Sailing Condition	726
Cargo Handling	40% x Hotel Load	12
Porting	12.5% Engine Power + Hotel Load	108.75

The formula above cannot be used literally as it depends on the type of ship being used. In this case, a general cargo ship without a crane is considered. Therefore, this formula can serve as a reference for similar types of ships. Based on the calculation table above, we can determine the required hydrogen weight using the following formula:

$$Weight = \frac{Power\ (kW)\ x\ Time\ (hour)\ x\ 0{,}00027778\ x\ Correction\ Factor}{Efficiency\ (\%)\ x\ LHV}$$

Here is a table with the results of the hydrogen requirements for each operation:

TABLE 8
EXPECTED HYDROGEN CONSUMPTION

Condition	Hydrogen Consumption (kg)
Sailing Condition	2728.1
Manoeuvring Condition	79.0
Cargo Handling	5.2
Porting	11.8
Total	2824.1

In this case, where the space is limited, liquid hydrogen tanks are more suitable. A higher amount of hydrogen can be stored, which will increase the days of operation. For this reason, research was only conducted for a liquid tank. Here is the selected tank:

TABLE 9
CRYCOLOR LIQUID HYDROGEN TANK SPECIFICATION

Cryolor Hydrogen Tank		
Horizontal Liquid Hydrogen Tank		
Total Net Capacity	18948	litters
LH2 Payloads	1500	kg
Length	5.59	m
Width	3.35	m
Height	3.02	m
Weight	10100	kg

Regarding that specification, the amount of tank we needed is 2 of liquid hydrogen.

D. Fuel Cell Calculation and Selection

In the market, there are several products that supply maritime standard fuel cells, the following are references to several fuel cells that will be used as a comparison.

TABLE 10
FUEL CELL SCPECIFICATIONS

Brand	Power Cell Group	Corvus Energy	Ballard	Genevos
Type	Marine System 200	Corvus Pelican Fuel Cell System	FC Wave	HPM-80
Approval	LR & DNV	DNV (Pending)	DNV	LR
Specification				
Dimension (mm)	730 x 900 x 2200	2159 x 1427 x 2320	1209 x 741 x 2195	1400 x 800 x 800
Weight	1070	3100	1000	300
Performance				
Rated Power	200	340	200	70
Voltage Output	550 - 1000	400 - 750	350 - 720	400 - 900
Efficiency	54%	unknown	54%	54%

Based on the above data, a comparative analysis of several factors is carried out, which are, voltage output, total volume, total weight, and load factor. The results of the comparison are below.

TABLE 11
FUEL CELL ANALYSIS COMPARISON

Brand	Power kW	Total Unit	Total Volume m3	Total Weight ton	Load Factor
Power Cell Group	200	4	5.78	4.28	91%
Corvus Energy	340	3	21.44	9.3	71.2%
Ballard	200	4	7.86	4	91%
Genevos	80	10	8.96	3.3	91%

Based on the above analysis, the Power Cell Group was chosen to be the selected fuel cell because it has the best value.

E. Battery Calculation and Selection

The battery calculation on the ship follows the DNV class regulations, which state: "Regarding class society, the Battery is to be capable of starting the main engine when in cold and ready to start condition. And the combined capacity of batteries is to be sufficient to provide within 30 min." Based on this, the following is the calculation table.

TABLE 12
BATTERY CALCULATION CASE 1

Total Starting Power	=	624.9	kW	Time	=	0.5	hour
Total Starting Energy	=	312.46	kWh				

No.	Brand	Energy kWh	Total Unit	Total Volume m3	Total Weight ton	Load Factor
1	Saft	16.128	20	11.73	2.56	96.9%
2	Lehmann Marine	93.6	4	2.85	3.6	83.5%
3	Leclanche	96	4	2.65	2.744	89.3%

Based on the calculations above, the Lehmann Marine battery is chosen. However, there is another option, which is to follow the design requirements, such as designing the battery capacity to be able to supply the entire sailing of the ship. If that is the case, then the battery requirement is:

TABLE 13
BATTERY CALCULATION CASE 2

LHV	=	33.3	kWh/kg	Required Energy	=	94128.3	kWh
Mass of LH2	=	2824.1	kg				

No.	Brand	Power kWh	Total Unit	Total Volume m3	Total Weight ton	Load Factor
1	Saft	16.1	5837	3425.3	747.1	100%
2	Lehmann Marine	93.6	1006	717.1	905.4	100%
3	Leclanche	96	981	650.9	673.0	99.9%

But in the case above, it is not very possible to apply it to the ship. So we will take the minimum requirement and the chosen battery is Leclanche.

F. Boil of Gas Calculation and Compressed Tank Selection

The calculation of the boil-off gas (BOG) determines how large the tank needs to be to accommodate the BOG. This calculation is performed by calculating the difference between the BOG generated and the BOG consumed by the fuel cell. For example, if the generated BOG is 9.5 kWh and the fuel consumption is 5.6 kWh, then we must accommodate the difference from the previous calculation, which is approximately 3.9 kWh. This calculation will be incorporated into a timetable that has a calculation period of 1 hour for sailing conditions and 15 minutes for other conditions. Here are the results of the BOG calculation timestamp table:

TABLE 14
BOG TIME TABLE

Type of Operation	**Time-stamp**	**Speed**	**Fuel Consumption**	**Boil of Gas**	**Difference**
		kn	**kg**	**kg**	**kg**
Cargo Handling in Klaipeda	17:55	0	0	0.31	0.3
	18:10	0	0.17	0.31	0.6
	18:25	0	0.17	0.31	0.8
	18:40	0	0.17	0.31	0.9
	18:55	0	0.17	0.31	1.1
	19:10	0	0.17	0.31	1.2
	19:25	0	0.17	0.31	1.4
	19:40	0	0.17	0.31	1.5
	19:55	0	0.17	0.31	1.6
	20:10	0	0.17	0.31	1.8

Type of Operation	**Time-stamp**	**Speed**	**Fuel Consumption**	**Boil of Gas**	**Difference**
		kn	**kg**	**kg**	**kg**
	20:25	0	0.17	0.31	1.9
	20:40	0	0.17	0.31	2.1
	20:55	0	0.17	0.31	2.2
	21:10	0	0.17	0.31	2.4
	21:25	0	0.17	0.31	2.5
	21:40	0	0.17	0.31	2.7
Porting Klaipeda S=4.96 NM	21:55	5	1.51	0.31	2.8
	22:10	5	1.51	0.31	1.6
	22:25	5	1.51	0.31	0.4
	22:40	5	1.51	0.31	0.0
	22:55	5	1.51	0.31	0.0

Fuel consumption remains constant and depends on the type of operation. According to the tank product manual, the boil-off gas (BOG) is always 1% of the tank volume. Based on the table above, the highest amount of BOG that must be accommodated is 2.8 kg. After this point, the BOG decreases as the operational power surpasses the BOG production, directing the excess BOG directly to the fuel cell. Based on that, here is the tank calculation for the BOG:

TABLE 15
TANK SELECTION

Total of Boil of Gas	=	2.06	kg
Tank Capacity	=	4.26	kg
Total Required Tank	=	1	

MAHYTEC		
CLDS10		
Total Net Capacity	850	liters
H2 Payloads (60 bar)	4.26	kg
Length	1.87	m
Width	0.84	m
Height	0.84	m
Weight (empty)	215	kg

G. Cooling System

Similar with the conventional cooling system, the cooling system utilizes a closed-loop system, which consists of LT (Low-Temperature), HT (High-Temperature), and SW (Seawater) components. The fuel cell will use both the HT and LT systems simultaneously. The HT system will be cooled by seawater in the central cooling system, while the LT system will be cooled by a simple cooling tank. After the HT system cools the fuel cell, the coolant will be directed to an evaporator, which can be used to reheat the LH2 (Liquid Hydrogen) that has just been converted to H2 (Hydrogen) gas due to the coil. This aims to accelerate the flow of H2 gas to the fuel cell. The following is a schematic diagram of the cooling system on the ship.

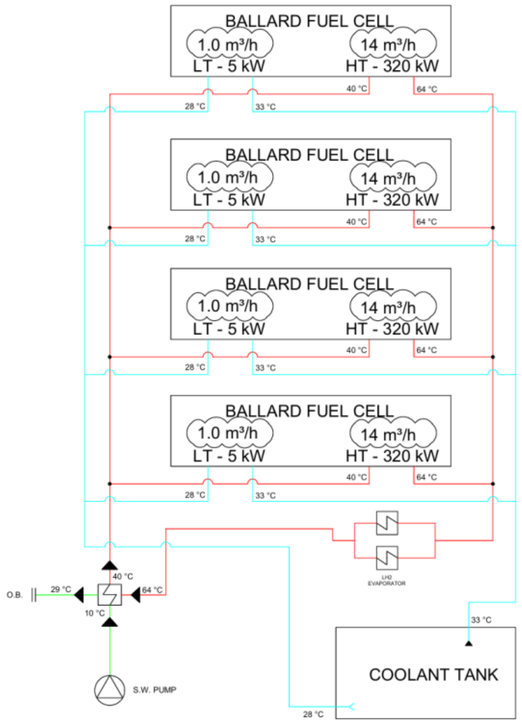

Figure. 1. Cooling system

H. Hydrogen System

Each liquid hydrogen (LH_2) tank on the ship is equipped with the following components:

- LH_2 Tank: Stores liquid hydrogen.
- Pressure Build Coil: Heats liquid hydrogen to convert it into gas for flow to the vaporizer.
- Cryogenic Pump: An alternative to the pressure build coil for transferring liquid hydrogen to the vaporizer.
- Vaporizer: Adjusts the temperature and pressure of gaseous hydrogen.
- Gas Handling Unit (GHU): Contains pressure regulation, protection, and temperature and pressure measurement devices.
- H_2 Tank: Stores boil-off gas (BOG).
- Control System: Manages the GHU.

This setup ensures efficient handling and conversion of liquid hydrogen to gaseous hydrogen for various uses on the ship.

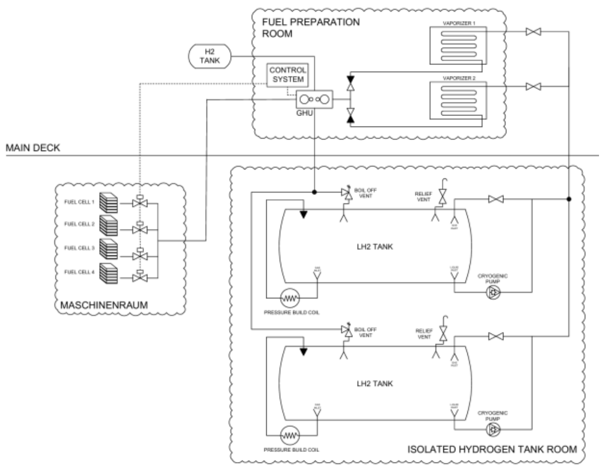

Figure. 2. Hydrogen system

I. Electrical System Transformation

The electrical system configuration has also changed, transitioning from using a generator along with an emergency generator to now utilizing fuel cells and batteries. The operation is very simple. When the fuel cell produces more power than the ship uses, the excess power is stored in the battery. Then, when more power is needed, the battery helps supply energy for a quicker power increase.

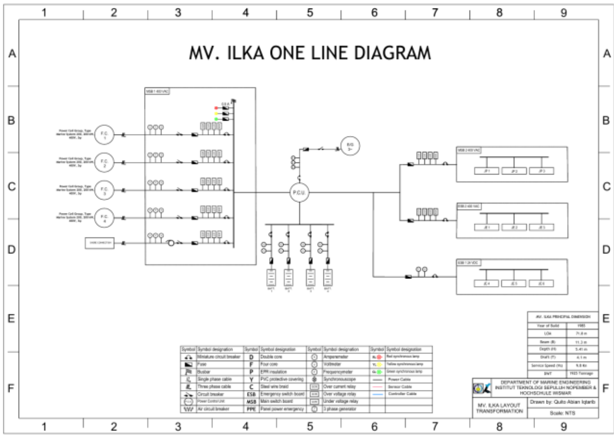

Figure. 3. One line diagram

J. Layout Transformation

After performing all the calculations above, we can plot the equipment and space into the old layout to create a new layout. Below is the new layout from several frame perspectives and views.

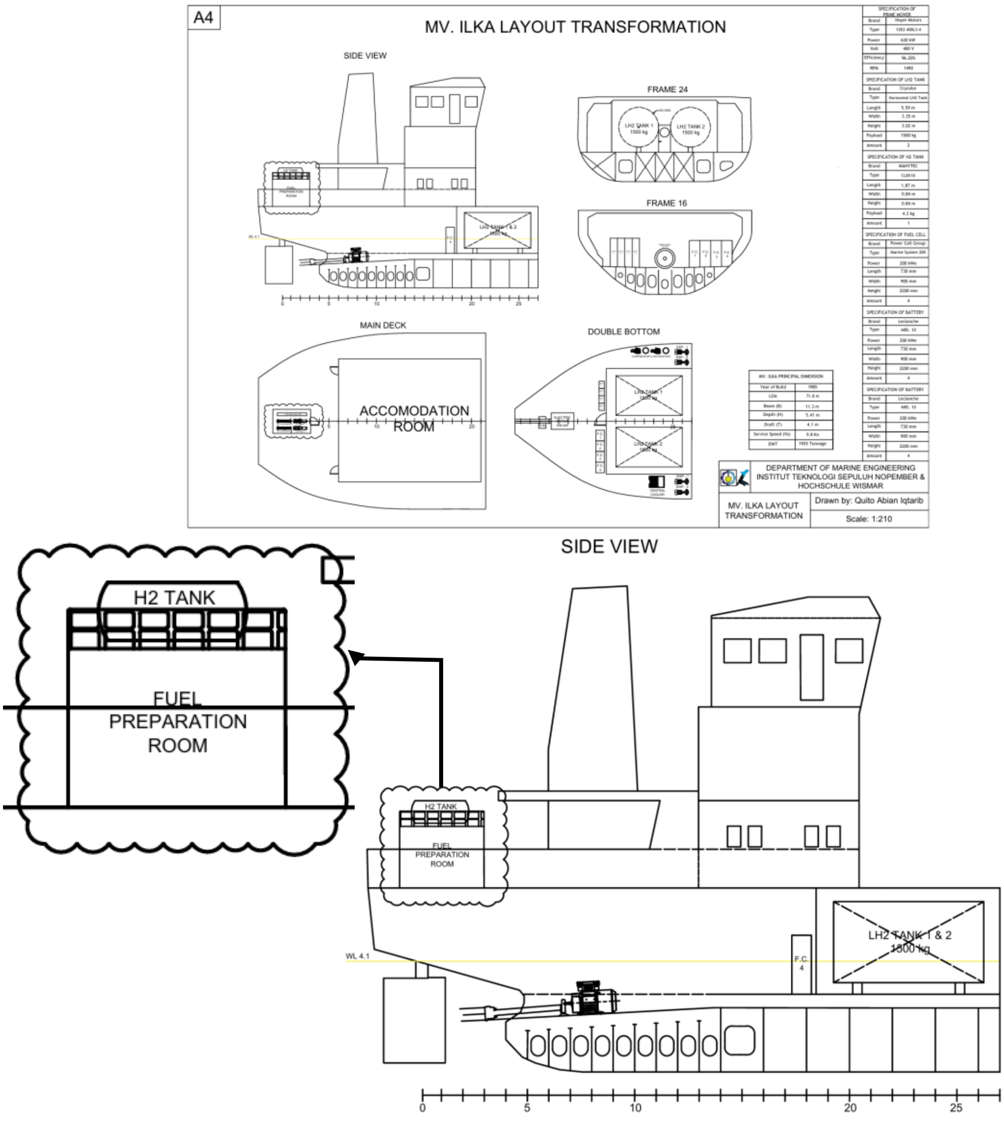

Figure. 4. MV new layout transformation

V. DESIGN REVIEW

After designing and calculating in the previous chapter, we can see that a ship with a total of 3000 kg of hydrogen on board is suitable for the general cargo ship MV on a three-day trip. However, typically a ship has a much longer endurance, such as 8-10 days for ships similar to original MV. If we set the same endurance, then this hydrogen fuel cell system is not suitable, as it requires more space than is available. Here are the overview:

TABLE 16
DESIGN REVIEW

Electric Motor Power	630 kW
LH2 Tank Specification	2 x 1500 kg
Fuel Cell	4 x 200 kW (L. Factor 91%)
Battery	4 x 96 kWh
H2 Tank Specification	1 x 4.2 kg (60 bar)

The entire fuel system from the previous design will be overhauled and replaced with a new system. Additionally, the propulsion system will be completely replaced as well, utilizing a 630 kW electric motor. The power calculation for each operation is based on manual calculations referenced from other general cargo ships without cranes. If you want to use the same calculations, ensure the principal dimensions of the ship are similar.

The reason liquid hydrogen is chosen is due to its higher energy density compared to compressed hydrogen, allowing us to store more fuel in the same volume. However, compressed hydrogen is also used because of the boil-off gas from liquid hydrogen. During a three-day voyage, the total boil-off gas (BOG) produced could be around 2.8 kg. To handle this, a hydrogen gas tank with a capacity of 4.26 kg will be used. The generated BOG will be directly supplied to the fuel cell, and any excess BOG will be stored in the tank.

VI. CONCLUSION

In conclusion, while a hydrogen fuel cell system with 3000 kg of hydrogen on board is suitable for the general cargo ship MV on a three-day trip, it is not feasible for the typical 8-10 day endurance of similar ships due to space constraints. Because the system is new, the old prime mover (diesel engine), generator, and several supporting systems need to be replaced with the new system. From the newly designed layout, it is evident that the new system can be integrated into the existing ship layout with some room modifications.

For further research, stability analysis and operational analysis for the ship powered by hydrogen fuel cells can be conducted.

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