REVIEW OF HYDROGEN EFFICIENCY IN MARINE PROPULSION SYSTEM

BY

OKPAMEN EUGENE ENG2002378

AMANDA OMIGIE ENG2002379

MOSES OKONKWO ENG2002377

SUMMITTED TO

THE DEPARTMENT OF MARINE ENGINEERING

FACULTY OF ENGINEERING

UNIVERSITY OF BENIN

SUPERVISED BY

DR. N. ENOMA.

NOVEMBER 2025

REVIEW OF HYDROGEN EFFICIENCY IN MARINE PROPULSION SYSTEM

BY

OKPAMEN EUGENE ENG2002378

AMANDA OMIGIE ENG2002379

MOSES OKONKWO ENG2002377

A RESEARCH PROJECT WRITTEN AND SUBMITTED TO THE DEPARTMENT OF MARINE ENGINEERING, FACULTY OF ENGINEERING, UNIVERSITY OF BENIN, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR A DEGREE OF BACHELOR OF ENGINEERING OF THE UNIVERSITY OF BENIN, BENIN CITY.

DECLARATION

We declare that:

This project work is based on a study undertaken by us in the Department of Mechanical Engineering, Marine Engineering, University of Benin under the supervision of Engr. Dr. N. ENOMA. This work has not been previously submitted for award of a degree elsewhere

All ideas and views are product of our personal research effort and all references to works of others has been duly acknowledged.

____________________ ____________________

OKPAMEN EUGENE Date:

____________________ ____________________

OKONKWO MOSES Date:

____________________ ____________________

OMIGIE AMANDA Date:

CERTIFICATION

This is to certify that the research project title **"REVIEW OF HYDROGEN EFFICIENCY IN MARINE PROPULSION SYSTEM"** was carried out by OKPAMEN EUGENE with matriculation number ENG2002378 in the Department of Marine Engineering, University of Benin, Benin City, Edo State.

____________________ ____________________

Engr. Dr. N. Enoma Date

Project Supervisor

____________________ ____________________

Engr. W. Jaja Date

Project Coordinator

____________________ ____________________

Engr. Prof. Osarobo. Ighodaro Date

Head of Department

ACKNOWLEDGEMENTS

Firstly, our appreciation goes to God Almighty for the strength he granted to us throughout this endeavor. For by strength shall no man prevail but he was there to be our guide and light.

We would like to thank our parents, family members for consistently spending their resources on me all through the entire process of this project. Their patience, support and sacrifices made us come this far.

We would also like to express our gratitude to our Supervisor Engr. Dr. N. Enoma for his guidance, Support, and feedback throughout this project.

We are also grateful to University of Benin for providing the necessary resources to conduct this project.

Additionally, we would like to thank the department of Mechanical Engineering, Marine Engineering, The H.O,D, our Course Advisor, our course mates and friends.

DEDICATION

This project is dedicated to almighty God. For His grace, wisdom, and strength that guided us to the successful completion of this project. We also extend this dedication to our families, supervisor, and colleagues for their unwavering support, motivation, and valuable contributions to our success.

ABSTRACT

This study reviews the efficiency of hydrogen as a sustainable fuel source in marine propulsion systems to address the urgent need for decarbonization in the shipping industry. Traditional marine fuels contribute significantly to global greenhouse gas and pollutant emissions; therefore, alternative, zero-emission solutions are critical.

The review demonstrates that hydrogen propulsion is a technically viable and highly efficient pathway toward zero-emission shipping. The findings provide critical data for naval architects, policy makers, and shipping companies, underscoring the necessity of investing in fuel cell technology and supporting hydrogen bunkering infrastructure to achieve the IMO's (International Maritime Organization) targets for a sustainable maritime sector.

TABLE OF CONTENT

Contents

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF STUDY

Over the years the maritime industry has been under increasing pressure to curb and control its environmental pollution that occurs by its shipping activities. The maritime industry is a significant contributor to global greenhouse gas emissions, accounting for approximately 2.9% of global CO2 emissions (Smith et al., 2015). This greenhouse gas emissions is as a result of vessels powered by traditional fossil fuel thereby causing global pollution. As concerns about climate change and air pollution continue to grow, and the pressure on the industry to reduce its environmental impact continues to increase, one promising solution is the adoption of alternative fuels and propulsion systems that can minimize emissions while maintaining efficiency and performance.

Hydrogen as an alternative fuel for marine propulsion system is very promising due to its zero emission operation. And hence will be a great factor to cure some of the drawbacks associated with diesel engines such as green gas emission. Hydrogen fuel cells have emerged as a potential game-changer in the quest for sustainable maritime transportation. By converting chemical energy into electrical energy, hydrogen fuel cells offer a zeroemission alternative to traditional fossil fuels (Kær, 2017).

1.2 WHAT ARE HYDROGEN FUEL CELLS?

A fuel cell is an electrochemical cell or device that converts the chemical energy of a fuel and an oxidizing agent into electricity through a pair of redox reaction. A hydrogen fuel cell works by combining hydrogen with oxygen to produce electricity, heat, and water.

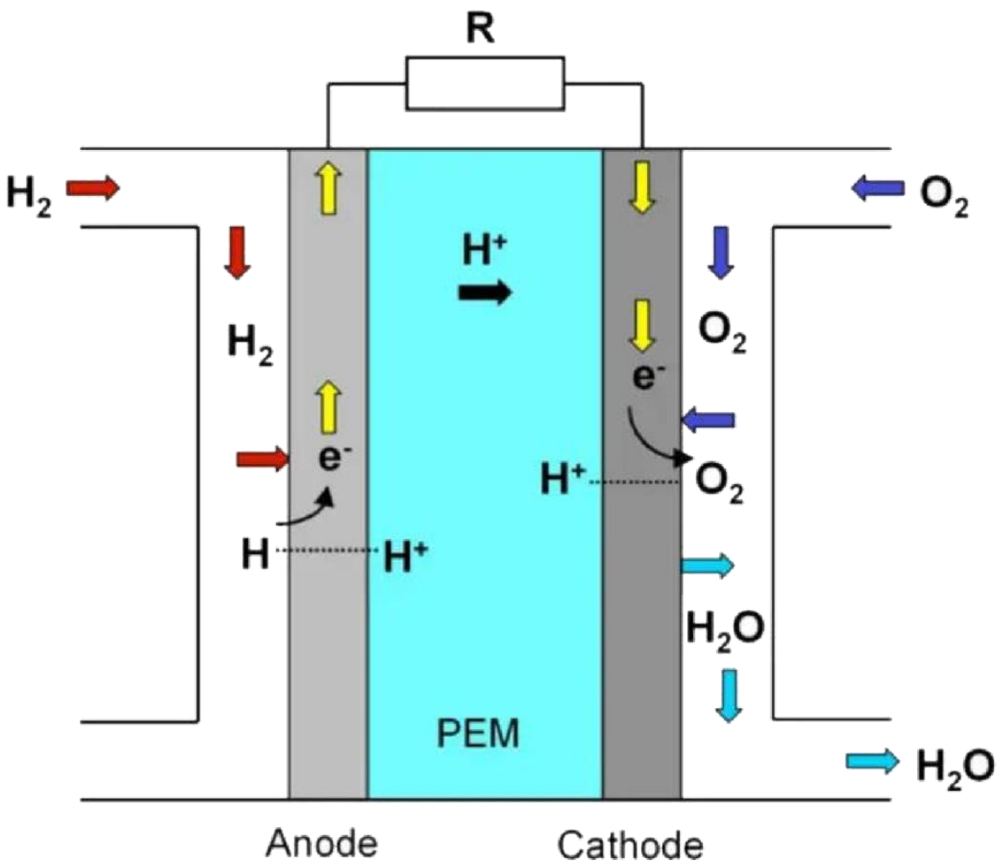


Figure 1 Hydrogen Fuel Cell

This technology has the potential to significantly reduce greenhouse gas emissions and air pollutants from ships, making it an attractive option for ship-owners and operators looking to comply with increasingly stringent environmental regulations. Despite the potential benefits, the adoption of hydrogen fuel cells in marine propulsion systems is still in its infancy. There are several challenges to overcome, including the production, storage, and handling of hydrogen, as well as the development of fuel cell systems that can meet the demanding requirements of maritime applications (Tronstad et al., 2017).

This project aims to examine the efficiency of hydrogen in marine propulsion system, examining its production, storage, technical, economical, safety and environmental feasibility of this technology. Analyzing the advantages and hindrances of hydrogen adoption.

This research seeks to contribute to the development of sustainable maritime transportation solutions.

1.3 AIMS AND OBJECTIVE

1.3.1 AIMS

The aim of this study is to review the efficiency of hydrogen in marine propulsion system.

1.3.1.2 OBJECTIVE

This study focuses on the investigation of hydrogen efficiency in marine propulsion system. Which includes:

i. Categorize Technologies and Efficiency Metrics: Systematically identify and categorize the primary hydrogen-based propulsion technologies.
ii. Quantify and Compare Energy Conversion Efficiency: Extract, quantify, and compare the reported energy conversion efficiencies (η) of the identified hydrogen propulsion systems across various marine operating conditions

iii. Synthesize Operational and System Constraints: Analyze and synthesize the qualitative findings regarding the key system-level factors, such as Balance of Plant requirements and thermal management impacts, that influence the net, real-world efficiency of hydrogen systems in shipboard applications.

iv. Identify Safety and Regulatory Influences: Review and summarize the consensus and conflicting reports on the major safety, logistical, and regulatory challenges (e.g., code compliance, storage boil-off) that directly affect the efficient deployment and overall viability of hydrogen in the maritime sector.

1.4 SCOPE OF THIS STUDY

This study will comprehensively examine and monitor the use of hydrogen in marine propulsion systems covering specific and key areas such as;

i. Method of hydrogen production

ii. Energy source for production

iii. Storage of hydrogen

iv. Hydrogen supply chain

v. Hydrogen fuel cell types

vi. Hydrogen fuel cell performance

vii. Hydrogen fuel cell system integration: Examining how fuel cells are integrated into marine propulsion systems and the challenges associated with this integration.

viii. Propulsion system efficiency: Evaluate the overall efficiency of the hydrogen fuel cell propulsion system. Including the efficiency of the fuel cell, power electronics, and motor.

ix. Ship performance: Examine the impact of hydrogen propulsion on ship speed, range, and fuel consumption.

x. Environmental Impact: Assess the environmental benefits of hydrogen-powered ships

xi. Economic Feasibility: Evaluate the cost – effectiveness of hydrogen powered ships compared to conventional diesel-powered ships, including the cost of fuel, infrastructure, and maintenance.

xii. Hydrogen safety

xiii. Technical challenges

xiv. Regulatory and policy issues

xv. Analyze existing hydrogen powered ships.

xvi. Focus on specific vessel types and their unique requirements for hydrogen propulsion.

xvii. This study will provide a snapshot of the current state of hydrogen fuel cell technology in marine propulsion systems.

1.5 LIMITATIONS OF THIS STUDY

This study’s scope is comprehensive and promising, but it is not without limitations, including;

i. Data Constraints: Existing data on hydrogen efficiency in marine propulsion systems are not too available hence will limit this study.

ii. Focus on specific fuel cell types: This study focuses on a particular fuel cell which might not be representative of other fuel cell types. This will limit the study's findings to a specific technology or application, also not account for variations in performance or efficiency across different fuel cell types and finally Potentially overlook emerging or alternative fuel cell technologies.

iii. Focus on current technology; This study focuses on the current type of hydrogen propelled technology and may not reflect future advancements. Hence will not account for future advancements or breakthroughs in the field. Will also Limit the study's findings to the current technological landscape. And then Potentially overlook emerging trends or innovations that may impact the feasibility and efficiency of hydrogen fuel cells in marine propulsion systems.

1.6 METHODOLOGY

i. Literature review and data collection: A comprehensive review of existing literature on hydrogen fuel cell in marine propulsion systems, including journal articles, conference papers, and industry reports. Collection of existing data on hydrogen fuel cell performance, efficiency, and emissions from literature and industry reports and expert interviews.

ii. In depth analysis of existing or proposed hydrogen fuel cell powered marine vessels, including their design, operation and performance.

1.7 EXPECTED OUTPUT

This report will include

i. Technical findings: This will include performance and efficiency data on hydrogen fuel cells in marine propulsion systems.

ii. Assessment of environmental impact

iii. Analysis of economic feasibility

iv. Identification of technical economic and operational challenges and opportunities

v. Identification of various production methods.

vi. Analysis of ship performance of hydrogen-based propulsion system

vii. Comparison of hydrogen fuel cells with traditional fossil fuel propulsion system and other alternative fuel propulsion system such as LNG, battery-electric system, hybrid systems, gas turbine propulsion systems etc.

CHAPTER TWO

LITERATURE REVIEW

2.1 BACKGROUND OF MARINE PROPULSION SYSTEMS

Marine propulsion systems are the essential mechanisms that convert energy into propulsive force, allowing a watercraft or vessel to move through water. Their fundamental role is to overcome the hydrodynamic resistance experienced by the vessel, ensuring a very efficient and controlled movement, steering, and maneuverability. Over time, the evolution of these systems reflects a continuous quest for greater speed, efficiency, reliability, and, increasingly, environmental sustainability. The earliest forms of marine propulsion were **oars and paddles**, harnessing human strength. Around 3000 BC, the innovation of **sails** revolutionized seafaring, allowing for longer voyages powered by wind.

The true mechanical revolution began in the late 18th century. In **1770, the steam engine** was adapted for maritime use, initially driving large **paddle wheels**. These early steamships, while groundbreaking, were less practical for open ocean travel. The 19th century saw a significant leap with the introduction of the **screw propeller**, a more efficient and robust method of generating thrust by pushing water backward. This was followed by the development of **steam turbines**, offering higher power and smoother operation for larger vessels.

The late 19th and early 20th centuries witnessed the advent of the **diesel engine**. Rudolf Diesel's invention provided a highly efficient and reliable power source, quickly gaining dominance in the marine industry due to its superior fuel economy compared to steam engines. The 20th century also saw the emergence of **gas turbines** for faster naval vessels and, for specialized applications like submarines and icebreakers, **nuclear reactors** producing steam for propulsion. Modern marine propulsion is predominantly driven by two-stroke or four-stroke diesel engines, often coupled with propellers, or in some cases, pump-jets.

2.2 THE EMERGENCE OF HYDROGEN PROPULSION: A RESPONSE TO ENVIRONMENTAL IMPERATIVES, AND A PATH TO REDUCING EMISSIONS.

The concept of using hydrogen as a fuel date back centuries, with early experiments in the 19th century demonstrating its potential in internal combustion engines. However, the widespread adoption of fossil fuels for transportation, including shipping, pushed hydrogen to the background for much of the 20th century.

The emergence of environmental concerns, particularly the issue of greenhouse gas emissions and air pollution from burning fossil fuels, became a major trigger for revisiting hydrogen as a viable energy source. This global push for cleaner energy has been the primary driver behind the rapid development of hydrogen propulsion systems in the marine sector.

The journey towards hydrogen marine propulsion largely revolves around the development and application of fuel cell technology. A fuel cell is an electrochemical device that converts the chemical energy of hydrogen (and an oxidant, typically oxygen from the air) directly into electrical energy, producing only water and heat as byproducts. This process is highly efficient and, crucially, produces zero tailpipe emissions of pollutants like NOx, SOx, and particulate matter, or greenhouse gases like CO2.

While the fundamental principles of fuel cells were established in the 19th century, their practical application for propulsion gained popularity in the latter half of the 20th century, particularly with advancements in materials science and engineering. Initial research and development focused on land vehicles and space applications (NASA used hydrogen fuel cells in the Gemini spacecraft in the 1960s), providing a foundation for marine adaptation. The real impetus for marine hydrogen propulsion began to accelerate in the early 21st century. As global regulations tightened and the industry sought sustainable alternatives to fossil fuels.

Early development in marine hydrogen propulsion often involved demonstration projects and pilot vessels. Governments, research institutions, and shipping companies started investing in exploring the feasibility and challenges of integrating hydrogen fuel cells into ships. Key milestones include:

i. **Early 2000s:** Increased academic and industrial research into marine fuel cell applications, addressing challenges such as hydrogen storage, safety protocols, and system integration in a harsh marine environment.

ii. **9:** Norway's "Viking Lady" offshore vessel incorporated a hydrogen fuel cell system as part of a hybrid setup, marking an early operational step.

iii. **0s onwards:** A surge in projects focusing on various types of hydrogen-powered vessels, including ferries, inland cargo ships, and specialized research vessels. These projects often involve collaboration between ship designers, fuel cell manufacturers, and infrastructure providers.

iv. **Recent Years (2020s):** The launch of the first commercial hydrogen-powered ferries and cargo vessels signifies a turning point, demonstrating the technology's readiness for practical application in specific segments. Notable examples include the MF Hydra in Norway (the world's first liquid hydrogen-powered ferry) and various hydrogen-powered inland barges in Europe.

2.3 PURPOSE OF THIS LITERATURE REVIEW

The primary purpose of this literature review is to conduct a comprehensive review into the efficiency of hydrogen as a fuel for marine propulsion systems. The review will systematically analyze existing research to address a critical knowledge gap in the transition to decarbonized shipping. It will not only examine the technological and engineering aspects of hydrogen propulsion but also consider the broader contextual factors that influence its viability. The ultimate goal is to synthesize current findings, identify key challenges, and highlight future research directions on the practical implementation of hydrogen-based solutions.

2.4 SCOPE OF THIS REVIEW

i. Hydrogen Production and storage

   a. Overview of hydrogen production methods
   b. Discussion of hydrogen storage options
   c. Challenges and limitations

ii. Fuel cell systems for marine propulsion

   a. Overview of fuel cell types
   b. Discussion of fuel cell system design and optimization
   c. Comparison with traditional propulsion systems

iii. Efficiency and performance Discussion of efficiency metrics

   a. Review of studies on hydrogen fuel cell system efficiency
   b. Analysis of factors affecting efficiency

iv. Economic feasibility and cost analysis of hydrogen propulsion systems.

v. Case studies and applications

   a. Review of existing or proposed hydrogen propelled marine vessels

2.5 HYDROGEN PRODUCTION AND STORAGE

The global push for decarbonization and the urgent need to address climate change have positioned hydrogen as a key clean energy vector for the 21st century. As the most abundant element in the universe, hydrogen offers a powerful, energy-dense alternative to fossil fuels, capable of transforming sectors that are difficult to electrify, such as heavy industry, long-haul transportation, and seasonal energy storage (Atilhan et al., 2021). However, hydrogen is not a primary source of energy but rather an energy carrier that requires production, storage and distribution before it can be utilized as fuel.

Hydrogen production methods are diverse and are often categorized by the carbon intensity of the process, leading to a "color-coded" classification system (MDPI, 2024). The choice of production method dictates the environmental footprint and the economic viability of the final hydrogen product.

2.5.1 Fossil Fuel-Based Production (Grey and Blue Hydrogen)

Historically, and currently, the majority of global hydrogen production relies on fossil fuels due to the maturity and cost-effectiveness of the technology.

2.5.1.1 Steam Methane Reforming (SMR):

This is the most common method, accounting for over 95% of hydrogen production in the United States and a significant share globally (Sürer & Arat, 2022). SMR involves a high temperature reaction between natural gas (CH_4) and steam to produce synthesis gas, a mixture of hydrogen (H_2) and carbon monoxide (CO). A subsequent water-gas shift reaction converts the CO into additional hydrogen and carbon dioxide (CO_2) (Atilhan et al., 2021). This process is highly efficient but results in substantial CO_2 emissions, classifying the output as "grey hydrogen."

Blue hydrogen is produced via the same SMR process as grey hydrogen, but it incorporates Carbon Capture, Utilization, and Storage (CCUS) technologies to capture the CO_2 emissions generated (EMSA, 2023). While this significantly reduces the carbon footprint compared to grey hydrogen, its environmental impact is not zero, as some emissions can escape during the process. The economic viability of blue hydrogen is tied directly to the cost and scale of CCUS infrastructure (MDPI, 2024).

The Process and Chemical Reactions of steam methane reforming

The SMR process takes place in a large, industrial-scale facility, typically consisting of a furnace and a series of reactors. It unfolds in the following stages:

i. Desulfurization: The natural gas feedstock must first be "cleaned" to prevent catalyst poisoning. Sulfur compounds, even in trace amounts, can severely degrade the performance of the catalysts used in the subsequent steps. The natural gas is passed through a desulfurization unit, often a bed of zinc oxide, which removes the sulfur content to a level of less than 1 ppm.

ii. The Reforming Reaction: This is the core of the SMR process. The desulfurized natural gas (CH_4) is mixed with high-temperature steam (H_2O) at a typical temperature range of 700°C to 1,000°C and a pressure of 3 to 25 bar. This mixture is then passed through a series of tubes filled with a nickel-based catalyst. The catalyst facilitates the highly endothermic reaction (meaning it requires a significant amount of heat input to proceed), as described by the following chemical equation:

iii. $CH_4+H_2O \rightarrow CO+3H_2 (\Delta H=+206\ kJ/mol)$

iv. This reaction produces a gas mixture known as synthesis gas or syngas, which is primarily composed of carbon monoxide (CO) and hydrogen (H_2), with small amounts of unreacted methane and carbon dioxide.

v. The Water-Gas Shift (WGS) Reaction: To maximize hydrogen yield and remove the undesirable carbon monoxide, the syngas is sent to a second reactor where the water-gas shift reaction occurs. This is a crucial step that converts the carbon monoxide produced in the first stage into more hydrogen. The CO reacts with additional steam over a different catalyst, typically an iron-chromium catalyst at a high temperature (around 350°C) and a copper-based catalyst at a lower temperature (around 200°C). This reaction is mildly exothermic (releases heat).

vi. $CO+H_2O \rightarrow CO_2+H_2 (\Delta H=-41\ kJ/mol)$

vii. The WGS reaction significantly increases the total hydrogen yield while converting the carbon monoxide into carbon dioxide (CO_2).

viii. Purification (Pressure Swing Adsorption - PSA): The final step is to purify the gas mixture, which now contains a high concentration of hydrogen along with CO_2 and other residual gases. The most common purification method is Pressure Swing Adsorption (PSA). The gas mixture is passed through a vessel containing a special adsorbent material that traps the impurities (CO_2, CO, and unreacted CH_4) at high pressure. When the pressure is released, the trapped gases are vented, leaving behind high-purity hydrogen (99.999%). The vented gas can often be used as fuel for the SMR furnace itself, improving the overall efficiency of the process.

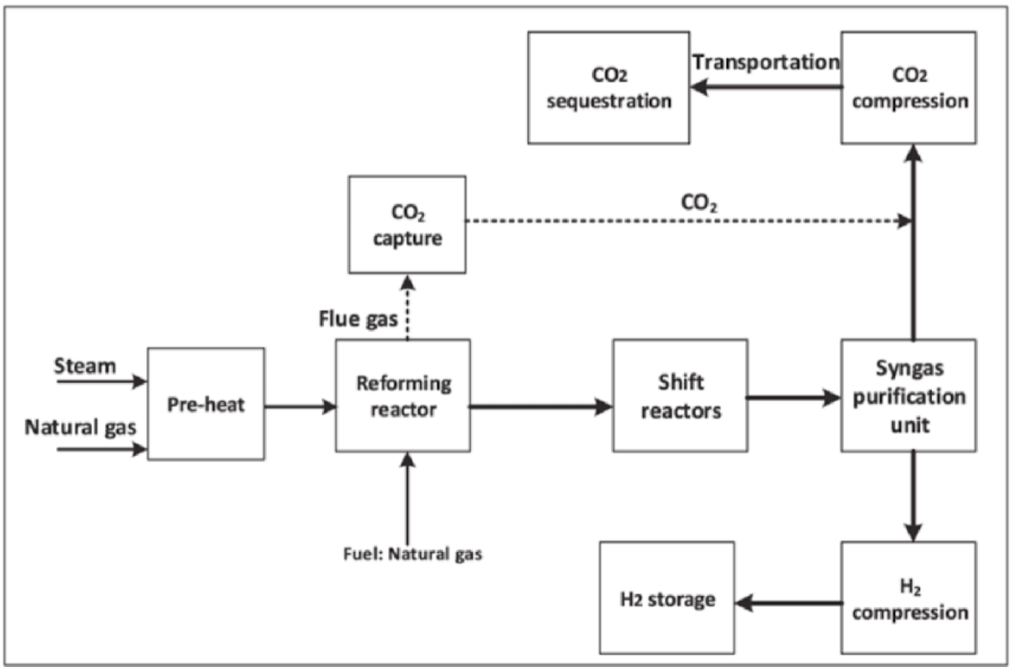


Figure 2 Schematic diagram of a steam reforming process with carbon capture

2.5.1.2 Partial Oxidation (POX):

Another fossil fuel-based method, POX, involves the sub-stoichiometric combustion of a hydrocarbon feedstock (natural gas, oil, or coal) with oxygen. This generates a synthesis gas that is then processed to produce hydrogen. POX is less common than SMR but can be used for a wider range of hydrocarbon feedstocks. The POX process is generally divided into two main types:

• Thermal Partial Oxidation (TPOX)

• Catalytic Partial Oxidation (CPOX).

Procedure for Thermal Partial Oxidation (TPOX)

i. TPOX is a non-catalytic process that requires very high temperatures to initiate and sustain the reaction. It is typically used for heavy, sulfur-rich feedstocks, as there is no catalyst to be poisoned. It unfolds in the following stages.

ii. Feedstock Preparation: The hydrocarbon feedstock (e.g., heavy fuel oil, coal slurry) is prepared and pressurized. Oxygen is supplied from an air separation unit (ASU) to ensure high purity and avoid nitrogen dilution. Steam is often added to the mixture to moderate the reaction temperature and suppress soot formation (OnePetro, 2025).

iii. Combustion Chamber: The feedstock, oxygen, and steam are fed into a refractorylined combustion chamber through a specialized burner. The chamber operates at temperatures above 1200°C and pressures ranging from 40 to 100 bar (SFC, 2024).

iv. The POX Reaction: Within the chamber, a rapid, flameless, and partial combustion of the hydrocarbon feedstock occurs. The exothermic reaction produces a hot syngas stream primarily composed of hydrogen (H_2) and carbon monoxide (CO), along with some carbon dioxide (CO_2) and unreacted methane.

v. Cooling and Soot Removal: The hot syngas exits the reactor and is immediately cooled in a waste heat boiler or a quench chamber. Rapid cooling "freezes" the chemical equilibrium, preventing further reactions and preserving the syngas composition. A subsequent step, such as a water wash, is used to remove any soot or ash produced during the process (OnePetro, 2025).

vi. Water-Gas Shift Reaction: The syngas is then routed to a water-gas shift (WGS) converter. Here, the carbon monoxide (CO) reacts with steam to produce additional hydrogen and carbon dioxide. This step is crucial for maximizing hydrogen yield and preparing the gas for purification.

   a. $CO + H_2O \rightarrow CO_2 + H_2 (\Delta H = -41 \text{ kJ/mol})$

vii. Purification: The final gas mixture, which now contains hydrogen and CO_2, is purified using technologies like Pressure Swing Adsorption (PSA) or amine scrubbing to achieve the required hydrogen purity.

While both follow the same basic principle, the use of a catalyst in CPOX significantly changes the operating conditions.

Procedure for Catalytic Partial Oxidation (CPOX)

i. CPOX uses a catalyst to facilitate the reaction, allowing it to occur at lower temperatures than TPOX. This is a more efficient process, but it is limited to feedstocks with very low sulfur conten t (typically less than 50 ppm) to avoid catalyst poisoning (MDPI, 2023).

ii. Feedstock Desulfurization: The hydrocarbon feedstock, typically natural gas or a light oil, must be meticulously desulfurized before entering the reactor to protect the catalyst.

iii. Catalytic Reactor: The cleaned feedstock and oxygen are passed through a reactor containing a precious metal catalyst, often based on rhodium (Rh), platinum (Pt), or nickel (Ni) (ResearchGate, 2024). The reaction temperature is significantly lower than in TPOX, ranging from 800°C to 900°C.

iv. The POX Reaction: The POX reaction occurs on the surface of the catalyst, producing a syngas stream. The catalytic nature allows for a more controlled reaction with higher selectivity towards hydrogen and carbon monoxide and reduced soot formation (MDPI, 2023).

v. Downstream Processing: Similar to TPOX, the syngas is cooled, passed through a water-gas shift converter to maximize hydrogen yield, and then purified using PSA or other methods.

2.5.1.3 Coal Gasification:

This method involves reacting coal with steam and oxygen at high temperatures and pressures to produce a synthesis gas. It is a major source of hydrogen in countries with abundant coal resources but is the most carbon-intensive of all production methods, resulting in "brown" or "black" hydrogen (MDPI, 2024).

The Coal Gasification Process for Hydrogen

The production of hydrogen from coal gasification is a multi-stage process that goes beyond the basic conversion of coal into syngas. It is a more involved procedure than other methods, requiring extensive downstream processing to isolate high-purity hydrogen. The overall process can be broken down into the following key steps:

i. Gasification and Syngas Production: The first stage involves the partial oxidation of coal within a gasifier. Pulverized coal is mixed with a controlled amount of an oxidant, typically oxygen or steam, and reacted at extremely high temperatures (up to 1,800°C) and pressures. The primary chemical reactions within the gasifier convert the carbon in the coal into a syngas composed mainly of carbon monoxide (CO) and hydrogen (H2) (MWCOG, 2007).

    a. Combustion Reaction: A portion of the coal is combusted with oxygen to provide the necessary heat for the entire process. The reaction is highly exothermic: 2C+O2

b. $\rightarrow 2CO$

c. Gasification Reaction: The primary hydrogen-producing reaction involves the reaction of carbon with steam, which is an endothermic process: $C+H_2O\rightarrow CO+H_2$

d. Boudouard Reaction: Unreacted carbon can also react with carbon dioxide to produce more carbon monoxide: $C+CO_2\rightarrow 2CO$

ii. Syngas Cleanup and Conditioning: The raw syngas from the gasifier contains impurities, including sulfur compounds (like H_2S), nitrogen compounds, and particulate matter (ash or soot). Before further processing, these contaminants must be removed to protect downstream catalysts and to meet environmental regulations. This is a critical advantage of gasification over direct combustion, as the high-pressure, concentrated gas stream makes pollutant removal more efficient (NETL, 2025).

iii. The Water-Gas Shift (WGS) Reaction: For hydrogen production, the syngas's H_2/CO ratio must be maximized. The syngas is passed through a shift reactor where the CO reacts with steam to produce additional hydrogen and carbon dioxide. This is a crucial step that distinguishes hydrogen production from other syngas applications. The reaction is exothermic and is typically performed in two stages (high-temperature and low-temperature shift) to maximize conversion (NETL, 2025). $CO+H_2O\rightarrow CO_2+H_2$

iv. Hydrogen Purification: After the WGS reaction, the gas stream is primarily composed of hydrogen and carbon dioxide. To obtain high-purity hydrogen, the CO2 and any remaining impurities are removed. The most common method is Pressure Swing Adsorption (PSA), which uses a solid adsorbent to capture impurities under high pressure and release them when the pressure is reduced. The result is hydrogen with a purity of up to 99.999% (IEA Bioenergy, 2025).

2.5.2. Renewable Energy-Based Production (Green Hydrogen)

Green hydrogen production, using renewable energy sources, is the ultimate goal for a sustainable hydrogen economy. This process uses electricity from renewable sources to power the electrolysis of water.

i. Water Electrolysis: Electrolysis splits water (H2O) into hydrogen and oxygen (O2) using an electric current. The efficiency of the electrolyzer and the cost of renewable electricity are the key determinants of green hydrogen's economic viability (RMI, 2025). There are three main types of electrolyzers:

ii. Alkaline Water Electrolysis (AWE): This is a mature technology using a liquid alkaline electrolyte (e.g., potassium hydroxide, KOH). AWE systems are durable and less expensive than other types, making them suitable for large-scale, long-term projects (MDPI, 2024).

iii. Proton Exchange Membrane (PEM) Electrolysis: PEM electrolyzers use a solid polymer electrolyte membrane. They are compact, can operate dynamically to follow the intermittent nature of renewable energy sources (like wind and solar), and produce very high-purity hydrogen, making them ideal for integration with renewable energy plants (FASTECH, 2024).

iv. Solid Oxide Electrolysis Cells (SOEC): SOEC systems operate at very high temperatures (700-1,000 °C) and are highly efficient. Their ability to utilize waste heat from industrial processes makes them a promising candidate for large-scale green hydrogen production in an industrial context (ACS Publications, 2021).

2.5.3 Emerging and Alternative Production Methods

Beyond the main production methods, research and development are exploring a variety of innovative technologies to diversify the hydrogen supply.

i. Biomass Gasification: This process uses heat and pressure to convert organic biomass (e.g., agricultural waste, wood) into a hydrogen-rich synthesis gas (MDPI, 2023). While technically a renewable method, its sustainability is debated due to land use, feedstock logistics, and associated emissions.

ii. Methane Pyrolysis (Turquoise Hydrogen): A more recent technology, methane pyrolysis, splits methane into hydrogen and solid carbon (graphite) at high temperatures. This method avoids CO2 emissions and offers a valuable solid byproduct. Its economic viability is still under development, but it shows promise as a bridge technology.

iii. Photobiological and Photocatalytic Methods: These advanced methods use sunlight to directly split water. Photobiological systems use microorganisms like algae or bacteria to produce hydrogen, while photocatalytic systems use semiconductor-based catalysts. Both are currently at a very early stage of research and are not yet commercially viable.

2.6 STORAGE OF HYDROGEN

Hydrogen's low volumetric energy density poses one of the most significant challenges to its widespread adoption. A large volume is required to store a small amount of hydrogen energy, necessitating innovative and efficient storage solutions (Sürer & Arat, 2022).

2.6.1. Physical-Based Storage

These methods rely on physical principles to contain hydrogen in a compact form.

i. Compressed Gas Hydrogen (CH2): This is the most common and mature storage method. Hydrogen gas is compressed to high pressures (350 or 700 bar) in robust composite tanks, typically Type IV tanks (carbon fiber reinforced polymer on a plastic liner) (MDPI, 2025). This method offers rapid refueling and is well understood from a safety and engineering perspective. However, the energy required for compression is substantial, and the bulky, heavy tanks can reduce payload capacity, particularly in mobile applications (FASTECH, 2024).

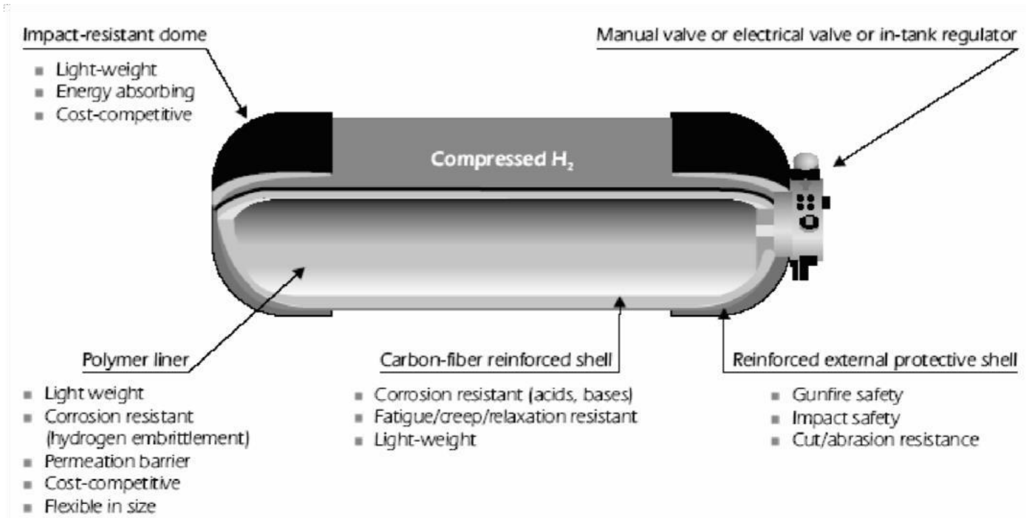


Figure 3 Compressed Hydrogen Gas Cylinder

Liquid Hydrogen (LH2): Liquefaction involves cooling hydrogen to a cryogenic temperature of −253 °C. This dramatically increases its volumetric density, making it suitable for large-scale, long-distance transport and applications like aerospace (FASTECH, 2024). The main drawbacks are the high energy penalty for liquefaction (up to 30% of the energy content) and the "boil-off" effect, where a small amount of the liquid evaporates daily, requiring specialized vacuum-insulated tanks.

ii. Cryo-Compressed Hydrogen: This hybrid approach combines the benefits of both compressed and liquid storage by storing hydrogen at cryogenic temperatures but at higher pressures than liquid hydrogen. It offers a higher energy density than compressed gas alone while mitigating some of the boil-off issues associated with pure liquid hydrogen (MDPI, 2025).

2.6.2. Material-Based Storage

This category of storage methods aims to address the shortcomings of physical storage by containing hydrogen within a solid material.

i. Metal Hydrides: Metal hydrides absorb hydrogen gas and store it within their crystal lattice through a chemical reaction. They offer high volumetric density and enhanced safety due to the lower operating pressures (MDPI, 2023). However, a key limitation is their low gravimetric density (mass of hydrogen stored per total mass of the system) and the energy required for the desorption of hydrogen, often at elevated temperatures (DOE, 2025).

ii. Complex Hydrides: These materials, such as sodium alanate (NaAlH4) and lithium borohydride (LiBH4), offer significantly higher gravimetric storage capacities than simple metal hydrides. Research in this area focuses on improving the kinetics of hydrogen absorption and desorption by using catalysts and reducing the high temperatures required for release.

iii. Porous Materials: Materials like Metal-Organic Frameworks (MOFs) and porous carbons store hydrogen by physically adsorbing it onto their large internal surface areas. These materials offer the potential for high storage capacity at relatively low pressures. However, their performance is highly sensitive to temperature and pressure conditions, and they are typically only effective at cryogenic temperatures (Fuel Cell Store, 2025).

iv. Liquid Organic Hydrogen Carriers (LOHCs): LOHCs, such as dibenzyl toluene, are liquid chemicals that can store hydrogen through a reversible hydrogenation/dehydrogenation reaction. They can be transported and stored in a manner similar to conventional liquid fuels, using existing infrastructure. The hydrogen is released on-site via a dehydrogenation process (ResearchGate, 2024). While LOHCs offer a convenient way to transport hydrogen, the process of loading and unloading the hydrogen requires significant energy and adds complexity.

2.6.3. The Hydrogen Supply Chain

The hydrogen supply chain is a complex network of activities that links hydrogen production to its end-use. Its development is a prerequisite for a functional hydrogen economy, and it involves production, transportation, and distribution

i. **Production and Siting:** The location of hydrogen production facilities is a key logistical challenge. Green hydrogen production sites need to be co-located with abundant renewable energy resources and water sources, which are often in remote locations, far from major demand centers (MDPI, 2024). This necessitates efficient and cost-effective transport solutions to bridge the geographical gap.

ii. **Transportation:** The mode of hydrogen transport depends on the volume, distance, and physical state of the hydrogen. The following are the possible means of hydrogen transportation:

iii. **Pipelines:** For large-scale, continuous delivery over long distances, dedicated hydrogen pipelines are the most efficient and economical option (Energy Tracker Asia, 2023). However, a dedicated hydrogen pipeline network is largely non-existent. The use of existing natural gas pipelines is a potential solution, but it requires significant modifications to address issues like hydrogen embrittlement (the degradation of pipeline materials by hydrogen) and potential leakages (MDPI, 2023).

iv. **Trucks and Trailers:** For smaller volumes and shorter distances, compressed hydrogen in tube trailers and liquid hydrogen in cryogenic tankers are used. While flexible, this method is significantly less efficient and more expensive than pipelines for high volumes (FASTECH, 2024).

v. **Maritime Shipping:** The use of marine vessels to transport hydrogen is essential. To transport a meaningful amount of hydrogen over an ocean, it must be converted into a more compact form. The primary modes for shipping hydrogen are:

a. **As a Cryogenic Liquid (LH_2):** The most direct method is to cool hydrogen gas to its boiling point of -253°C (-423°F). This liquefaction process increases its volumetric density by approximately 800 times. The liquid hydrogen is then transported in highly insulated, spherical tanks on specialized cryogenic vessels.

b. **As a Chemical Carrier:** A more common approach is to chemically bond hydrogen with another element or compound to create a liquid that is easier to handle. The most prominent examples include:

c. **Ammonia (NH_3):** Hydrogen is combined with nitrogen to create ammonia, a liquid that can be transported at a much warmer temperature (-33°C). The global fleet of ammonia tankers can be adapted for this purpose, leveraging existing infrastructure (Gas Turbine World, 2024). The hydrogen is released from the ammonia at the destination.

d. **Liquid Organic Hydrogen Carriers (LOHCs):** These are organic, oil-like compounds that can absorb and release hydrogen. They can be transported at ambient temperatures using conventional tankers, offering a high-density, low-risk shipping solution.

In all cases, the hydrogen "gas" is not transported as a gas but rather as a liquid or a component of a liquid to make the journey economically and logistically feasible.

vi. **Distribution and Refueling Infrastructure:** The "last mile" of the hydrogen supply chain involves distributing the fuel to end-users, such as vehicle refueling stations and industrial sites. This requires a new network of hydrogen dispensers, storage tanks, and on-site compressors. The high cost of this new infrastructure is a major barrier, and coordinated investment from both the public and private sectors will be necessary to build a viable network.

2.7 HYDROGEN FUEL CELL SYSTEMS FOR MARINE PROPULSION.

A fuel cell converts the chemical energy of a fuel and an oxidant directly into electrical energy through an electrochemical reaction, producing only water and heat as byproducts. This direct conversion process is fundamentally more efficient than combustion engines, which must first convert chemical energy into thermal and then mechanical energy, losing a significant portion as waste heat (Spectra Fuels, 2024).

A hydrogen fuel cell converts chemical energy into electrical energy by reacting hydrogen with oxygen. The process produces electricity, water, and heat as byproducts. Unlike a battery, which stores all its reactants internally, a fuel cell requires a continuous supply of fuel and oxidant to generate power (NY Engineers). This ability to produce electricity as long as fuel is supplied is a key feature that makes fuel cells ideal for applications requiring continuous power output.

2.7.1 How a Hydrogen Fuel Cell Works

Every fuel cell consists of three primary components: an anode (the negative electrode), a cathode (the positive electrode), and an electrolyte, which is a material that conducts ions between the two electrodes while remaining electrically insulated.

i. Fuel Supply to the Anode: A fuel, such as hydrogen or a hydrocarbon, is supplied to the anode.

ii. Oxidant Supply to the Cathode: An oxidant, typically oxygen from the air, is supplied to the cathode.

iii. Electrochemical Reaction: At the anode, a catalyst causes the fuel to undergo an oxidation reaction, which separates the fuel molecules into ions and electrons. The ions travel through the electrolyte to the cathode, while the electrons are forced to travel through an external circuit, creating an electric current that can be used to power a device.

iv. Reaction at the Cathode: At the cathode, another catalyst causes the ions, electrons, and oxidant to react, forming a byproduct, which is typically water (FuelCell Energy).

This general working principle is shared by all fuel cell types, though the specific chemical reactions, operating temperatures, and materials used can vary significantly. The fundamental difference between fuel cell types lies in the electrolyte and the corresponding ion that it conducts. This difference dictates the operating temperature, the types of catalysts required, and the fuel flexibility of the system.

2.7.2 Fuel Cell Types for Marine Applications

While several types of fuel cells such as (hydrogen fuel cells (HFCs), direct methanol fuel cells (DMFCs), solid oxide fuel cells (SOFCs), molten carbonate fuel cells (MCFCs), phosphoric acid fuel cells (PAFCs), alkaline fuel cells (AFCs), proton exchange membrane fuel cells (PEMFCs), direct ethanol fuel cells (DEFCs), biological fuel cells), exist only a few are considered viable for marine applications due to the demanding nature of the operating environment, including constraints on space, weight, and safety. The selection of a fuel cell type is a trade-off between its operating temperature, efficiency, fuel flexibility, and power density. The following are the considerable fuel cell applicable to marine propulsion system:

2.7.2.1. Proton Exchange Membrane Fuel Cell (PEMFC)

PEMFCs are the most common type of fuel cell used in marine propulsion today, primarily for small to medium-sized vessels, ferries, and auxiliary power units (APUs). They use a solid polymer electrolyte membrane that conducts protons from the anode to the cathode.

The basic structure of a PEMFC consists of three main components: an anode, a cathode, and a polymer electrolyte membrane (PEM) sandwiched between them. The anode and cathode are electrodes coated with a catalyst, typically platinum.

Working Principle

1. The Anode Side

a. Hydrogen gas (H2) is fed into the anode, which is the negative electrode of the fuel cell.

b. The gas diffuses through a porous gas diffusion layer to the catalyst. At this point, the catalyst (platinum) facilitates a crucial reaction: it splits the hydrogen molecules into positively charged protons (H+) and negatively charged electrons (e−).

c. The reaction at the anode is an oxidation half-reaction:

a. $2H_2 \rightarrow 4H^+ + 4e^-$

d. The newly formed protons are small enough to pass through the proton-exchange membrane. The electrons, however, are blocked by the membrane and are forced to travel through an external circuit to reach the cathode (Biolin Scientific). This flow of electrons through the external circuit is the electricity that powers an electrical load, such as a motor or a light bulb.

2. The Cathode Side

a. Simultaneously, oxygen gas (O_2), typically from the air, is supplied to the cathode, the positive electrode.

b. The electrons, having completed their journey through the external circuit, arrive at the cathode.

c. At the cathode's catalyst, oxygen molecules react with the incoming protons (that passed through the membrane) and the electrons (that came from the external circuit).

d. This is a reduction half-reaction, and its product is water:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

3. The Overall Reaction and Byproducts

The complete chemical reaction within the fuel cell combines the anode and cathode reactions. The overall result is a highly efficient conversion of hydrogen and oxygen into electricity, with water and a small amount of heat as the only byproducts (FCHEA).

The overall chemical reaction is:

$2H_2 + O_2 \rightarrow 2H_2O + \text{Electrical Energy} + \text{Heat}$

The continuous supply of hydrogen to the anode and oxygen to the cathode allows the fuel cell to operate continuously, producing electricity without the need for recharging. This makes it a clean, quiet, and highly efficient alternative to traditional energy sources (TWI Global).

2.7.2.2 Components of The Proton Exchange Membrane Fuel Cell

The functionality of the fuel cell depends on a few key components beyond the anode, cathode, and electrolyte:

i. Bipolar Plates: These plates are essential for assembling individual fuel cells into a "stack" to achieve a usable voltage. They provide electrical conduction between the cells and contain channels to distribute hydrogen and oxygen gas over the electrodes (U.S. Department of Energy).

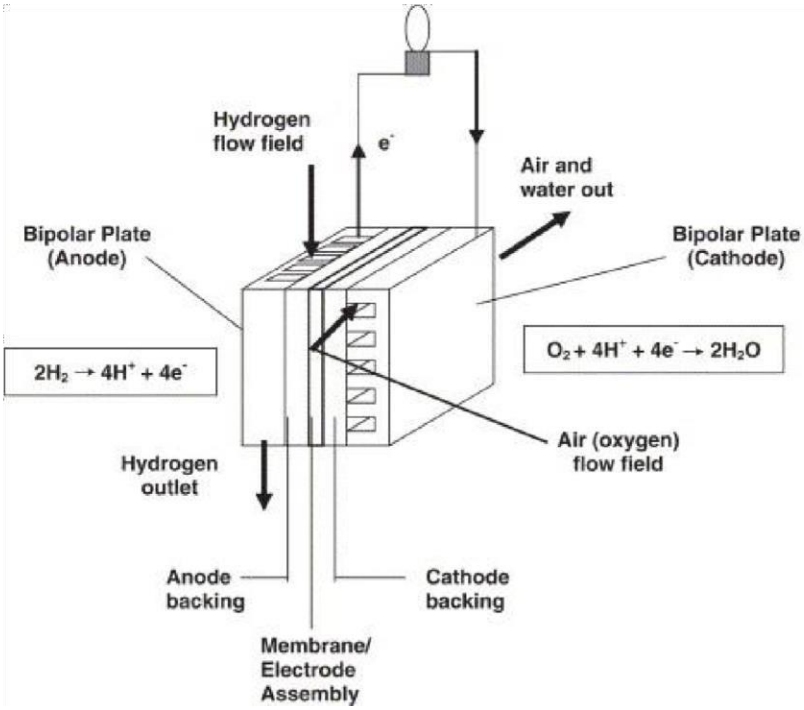


Figure 4 Bipolar plate for PEM Fuel Cell

ii. Gas Diffusion Layers (GDL): These porous carbon-based layers sit on either side of the membrane and facilitate the transport of gases to the catalyst layers while also helping to manage the water produced by the reaction (U.S. Department of Energy).

iii. Catalyst Layers: Typically made of platinum nanoparticles coated onto carbon paper, the catalysts at both the anode and cathode are crucial for speeding up the electrochemical reactions, enabling the efficient splitting of hydrogen and the formation of water.

Suitability for Marine Use.

PEMFCs operate at a low temperature (60-100°C), allowing for fast startup and shutdown times, which is crucial for vessels that require dynamic power response. Their high power density—both volumetric and gravimetric—makes them well-suited for applications where space is limited. The system is also highly modular, allowing multiple stacks to be combined to meet a vessel's power requirements (IDTechEx, 2023).

2.7.2.3. Solid Oxide Fuel Cell (SOFC)

SOFCs are high-temperature fuel cells that are gaining interest for larger vessels, such as cruise ships and cargo vessels. They use a solid ceramic material as the electrolyte, which conducts negative oxygen ions.

The Working Principle

The basic structure of an SOFC consists of a solid ceramic electrolyte positioned between two porous electrodes: the anode and the cathode. Unlike other fuel cells that conduct positive ions, an SOFC's electrolyte conducts negatively charged oxygen ions (O2−).

1. The Cathode (Oxygen Electrode)

a. Oxidant, typically air, is fed into the cathode.

b. At the cathode's triple phase boundary—the point where the air, electrode, and electrolyte meet—oxygen molecules (O_2) from the air gain electrons from the external circuit and are reduced to negatively charged oxygen ions (O^{2-}).

c. The cathode reaction is a reduction half-reaction:

$$O_2 + 4e^- \rightarrow 2O^{2-}$$

2. The Electrolyte (Solid Ceramic)

a. The electrolyte is a dense ceramic material, most commonly Yttria- stabilized zirconia (YSZ), which is an ionic conductor but an electronic insulator (Wikipedia, 2025). This means it allows the oxygen ions to pass through but blocks the electrons, forcing them to travel through the external circuit.

b. The high operating temperature of an SOFC (600-1000°C) is necessary to make the ceramic electrolyte conductive enough to allow for the efficient migration of oxygen ions from the cathode to the anode.

3. The Anode (Fuel Electrode)

a. A fuel, in this case hydrogen (H_2), is supplied to the anode.

b. The oxygen ions that have migrated through the electrolyte react with the fuel at the anode. For hydrogen fuel, the reaction is as follows:

$$2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$$

c. This oxidation reaction releases water vapor as a byproduct and produces electrons. These electrons are released into the external circuit, completing the electrical loop and generating power (netl.doe.gov).

Overall Reaction

The overall reaction within an SOFC combines the anode and cathode reactions.

$2H_2 + O_2 \rightarrow 2H_2O +$ Electrical Energy+ Heat

Suitability for Marine Use:

The unique properties of SOFCs provide several compelling advantages that make them a strong candidate for marine power systems, particularly for large vessels.

i. Exceptional Electrical Efficiency: SOFCs boast very high electrical efficiencies, typically ranging from 60% to 65% (ResearchGate, 2024). This is significantly higher than the efficiency of conventional marine diesel engines, which rarely exceed 50%. This high efficiency translates directly into lower fuel consumption and reduced operating costs over time.

ii. High Fuel Flexibility: One of the most significant benefits of SOFCs for the shipping industry is their ability to operate on a variety of fuels. Due to their high operating temperature, SOFCs can internally reform hydrocarbons and alcohols, allowing them to use fuels like liquefied natural gas (LNG), methanol, or even ammonia without the need for a separate, external reformer (MDPI, 2024; Nautilus

Project, 2023). This flexibility is crucial for a global industry that relies on a diverse and evolving fuel infrastructure. The ability to use LNG, a fuel that already has an established bunkering network, is a major interim advantage on the path to fully carbon-free fuels.

iii. Combined Heat and Power (CHP) Potential: The high-grade waste heat produced by SOFCs can be recovered and used for a variety of onboard needs, such as heating, air conditioning, or freshwater desalination. When integrated into a CHP system, the overall efficiency of an SOFC can be boosted to over 80%, providing a highly efficient and self-sufficient power plant for large vessels like cruise ships (ResearchGate, 2024). A case study on a cruise ship found that an SOFC plant could significantly reduce CO2, SOx, and NOx emissions while providing sufficient power for hotel loads and other services (ResearchGate, 2021).

iv. Environmental Benefits: SOFCs produce very low to zero local emissions, including NOx, SOx, and particulate matter, which are major environmental concerns in port areas and emission control zones. This makes them a key technology for achieving compliance with strict IMO regulations (TU Delft Research Portal, 2025).

2.7.3 Performance Comparison of PEMFC and SOFC for Marine Applications

The choice between PEMFC and SOFC for a specific marine application depends on a careful evaluation of their performance metrics in the context of the vessel's operational profile

CHARACTERISTIC	PEMFC	SOFC
Electrical Efficiency	50-70%	60-65% (electrical); >80% (CHP)
Power Density	Very high (up to 600 W/kg)	Lower (typically < 70 W/kg)
Operating Temperature	60-100°C (low)	500-1,000°C (high)
Startup Time	Fast (minutes)	Very slow (hours)
Fuel Purity	Requires high-purity H_2; sensitive to impurities	Highly fuel flexible; tolerant of impurities; can use natural gas, ammonia, methanol.
Catalyst	Platinum (expensive)	Non-precious metals (lower cost)
Vibration/Shock Tolerance	Good, due to solid electrolyte	Can be brittle; more sensitive to mechanical stress
Maintenance	Lower-temperature components are easier to maintain.	High-temperature components require specialized maintenance.

2.7.4 Hydrogen Fuel Cell System Integration into Marine Propulsion

Integrating a fuel cell into a ship's power and propulsion system is a complex engineering task that goes far beyond simply replacing a diesel engine with a fuel cell stack. The entire system, known as the "Balance of Plant" (BOP), must be designed to safely and efficiently manage fuel, air, thermal energy, and electrical power.

Unlike a conventional diesel engine, a hydrogen fuel cell does not provide a direct mechanical connection to the propeller. Instead, it serves as a generator of electricity, which is then used to power an electric motor that drives the propeller. The most effective and widely adopted system architecture for this is a fuel cell-battery hybrid system. This design leverages the strengths of both technologies while mitigating their weaknesses, creating a robust and efficient power plant. The step-by-step connection flow for a typical hybrid system is as follows:

1. Step 1: Hydrogen Storage: The process begins with the onboard storage of hydrogen fuel. For a marine application, this is typically done using high-pressure compressed gas tanks, although cryogenic liquid hydrogen is also being explored. The hydrogen tanks are located in a dedicated, well-ventilated space designed to meet stringent safety regulations from bodies like the IMO and classification societies such as ABS (ENR, 2023).
2. Step 2: Fuel Cell Stack: The stored hydrogen is fed from the tanks through a series of valves and pressure regulators to the fuel cell stack. The stack, which consists of

multiple individual fuel cells, is where the primary electrochemical conversion of hydrogen into electricity occurs.

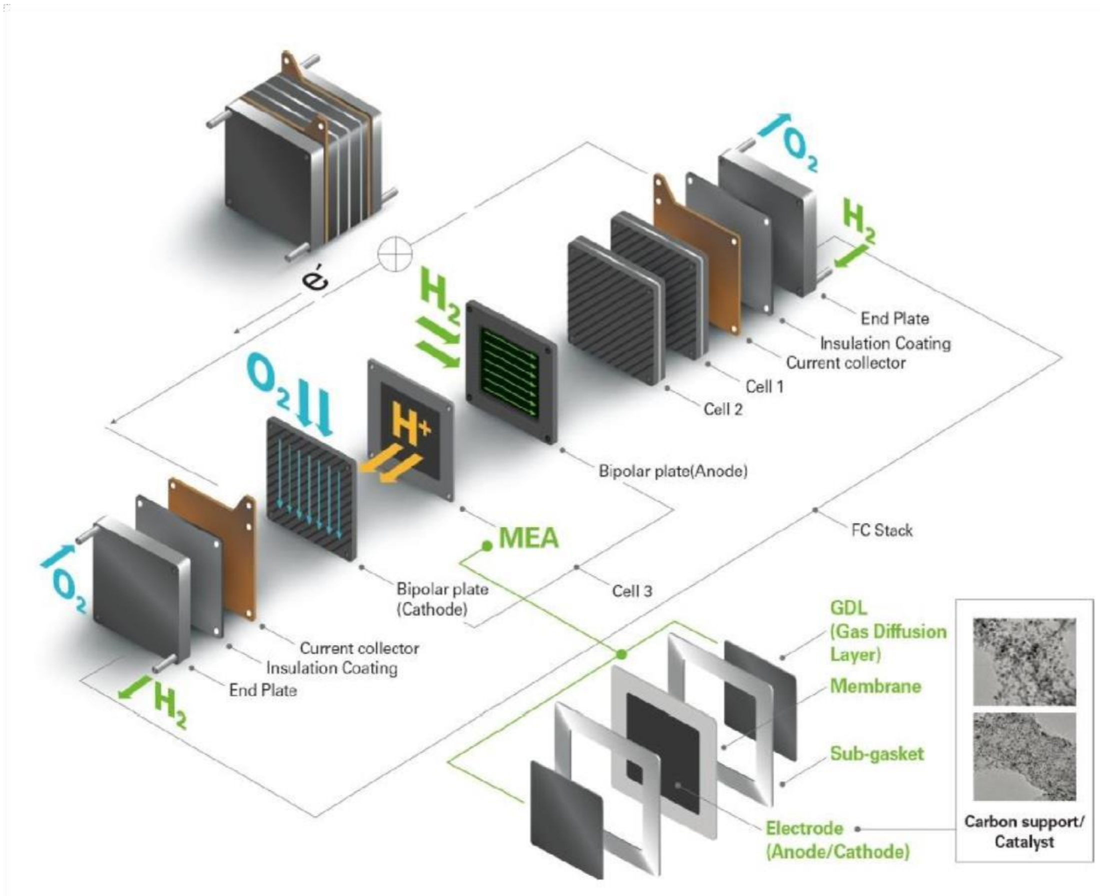


Figure 5 Schematic of fuel cell stack and components

3. Step 3: The Balance of Plant (BOP): The fuel cell stack is not a standalone system. It requires a sophisticated Balance of Plant (BOP) to function. The BOP includes crucial subsystems that manage the flow of reactants, regulate temperature, and ensure safe operation.

Air Supply Subsystem: An air compressor draws in and pressurizes ambient air to supply oxygen to the fuel cell cathode. This subsystem also manages the humidity and temperature of the air stream for optimal performance (AVL, 2024).

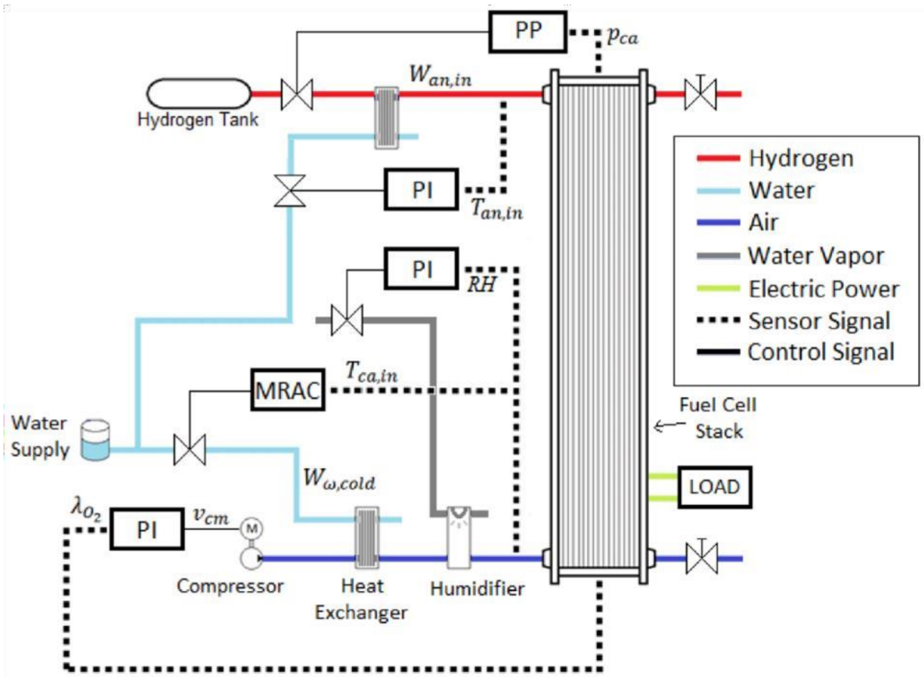


Figure 6 Air Supply Subsystem In A PEMFC With Balance Of Plant Simulation

Thermal Management Subsystem: The fuel cell reaction produces a significant amount of waste heat. A cooling circuit, often with a heat exchanger, removes this heat to maintain the stack at its ideal operating temperature. In certain applications, this waste heat can be captured and used for onboard heating or desalination, improving overall system efficiency

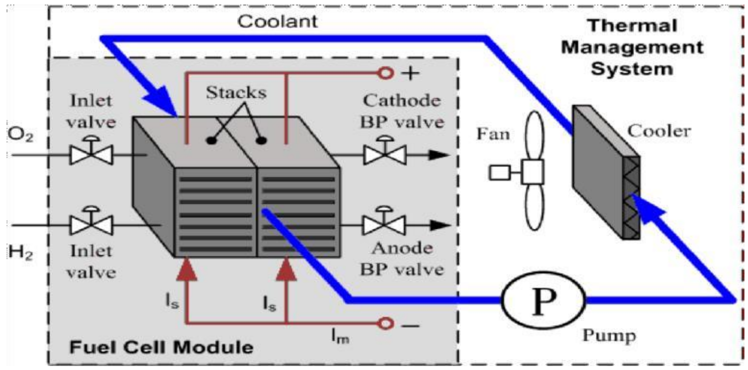
i. 

Figure 7 PEMFC With A Thermal Management System

Water and Gas Management Subsystem: This includes components like water separators to remove water produced by the reaction and an anode gas recirculation system to improve hydrogen utilization (AVL, 2024).

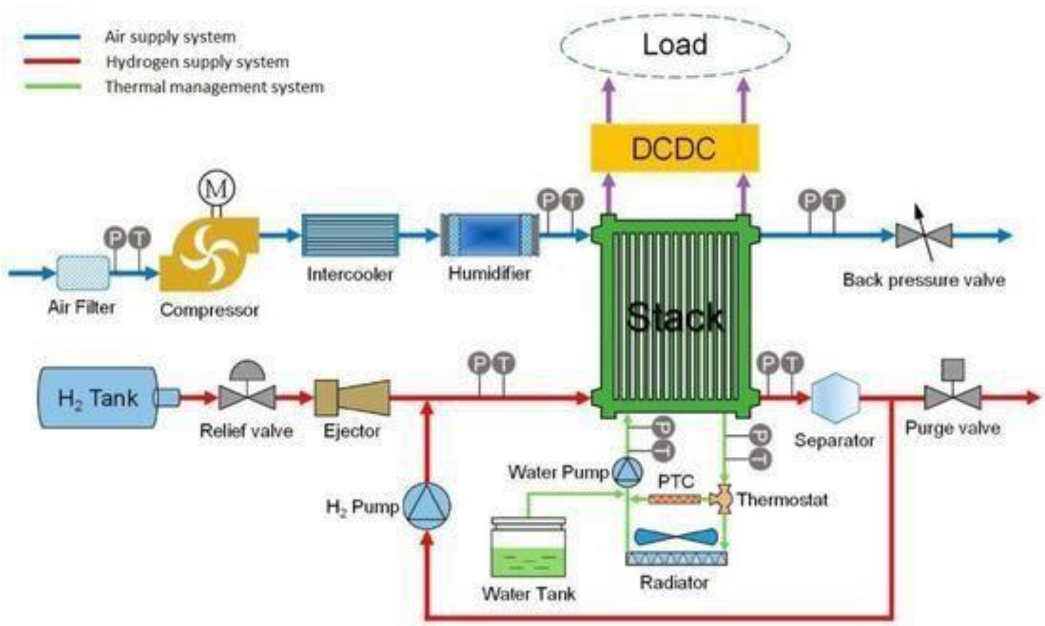


Figure 8 Schematic diagram of the pemfc showing its Components

4. Step 4: Power Conversion and Distribution: The electricity generated by the fuel cell is direct current (DC). This DC power is then sent to a power conditioning unit (PCU) or a DC-DC converter. The PCU's role is to boost the relatively low voltage from the fuel cell stack to a higher, more usable voltage for the ship's electrical grid.

5. Step 5: Integration with an Energy Storage System: The fuel cell is connected to a high-power battery bank via a bidirectional DC-DC converter. This connection is the cornerstone of the hybrid system. The battery serves as a buffer, performing several critical functions (ResearchGate, 2024):

    a. Peak Shaving: Fuel cells are slow to respond to rapid changes in power demand, such as during acceleration or maneuvering. The battery instantly supplies the necessary peak power, protecting the fuel cell from damaging load fluctuations and allowing it to operate at a stable, highly efficient output (CiteSeerX, 2023).

    b. Load Leveling: The battery absorbs power during periods of low demand and releases it when power is needed, allowing the fuel cell to run at its optimal efficiency point.

    c. Regenerative Braking: In electric propulsion systems, the battery can capture kinetic energy generated when the vessel slows down and store it for later use.

d. Black Start Capability: The battery provides the power needed to start up the fuel cell system and its auxiliary components, eliminating the need for a separate power source.

6. Step 6: Power to the Propulsion Motor: The high-voltage DC bus then supplies power to the propulsion motor via an inverter. The inverter converts the DC power into the variable frequency alternating current (AC) required to drive the electric motor at a wide range of speeds.

2.7.4.2. Electrical Grid Architecture: DC vs. AC

The choice of the vessel's electrical grid is a critical aspect of system integration. While traditional ships use an AC grid, the native DC output of a fuel cell makes a DC grid a highly efficient and logical choice for hydrogen-powered vessels.

i. **DC Grid Advantages:** A DC distribution system can be more efficient, lighter, and more compact. It eliminates the need for bulky transformers and rectifiers, as power from the fuel cell and battery can be directly integrated. This simplification reduces energy losses and saves space and weight, a critical factor on any vessel. The DC grid also offers greater flexibility for connecting other DC-based energy sources like solar panels and simplifies the architecture of hybrid systems (ABB, 2025).

ii. **AC Grid Integration:** If the vessel uses a conventional AC grid, the fuel cell's DC output must be converted to AC via an inverter before being distributed to the ship's loads. This adds complexity and introduces conversion losses, but it can be necessary for compatibility with existing ship systems or for vessels with a large AC auxiliary load.

2.7.4.3. The Energy Management System (EMS)

The seamless operation of the entire hybrid system is overseen by a sophisticated Energy Management System (EMS). The EMS is the "brain" of the power plant, continuously monitoring the state of charge of the battery, the power demand from the propulsion motor, and the performance of the fuel cell stack. It executes complex control strategies to optimize power distribution in real-time (Trepo, 2025).

i. The EMS's functions include:

ii. **Power Splitting:** Deciding how much power to draw from the fuel cell and how much to draw from or store in the battery, based on the load profile of the vessel.

iii. **Load Following:** Ensuring that the system can respond to sudden changes in power demand while protecting the fuel cell from damaging transient loads.

iv. **Efficiency Optimization:** Keeping the fuel cell operating in its most efficient power range to reduce hydrogen consumption and prolong its lifespan (PSE Community.org, 2023).

v. **Fault Detection:** Monitoring the system for potential faults and initiating a safe shutdown or load shedding if a critical issue is detected.

2.8 EFFICIENCY AND PERFORMANCE OF A HYDROGEN PROPULSION SYSTEM

The overall efficiency of a hydrogen fuel cell propulsion system is a critical metric that determines its viability and competitiveness against conventional power sources. Unlike the efficiency of a combustion engine, which is a single value, the total efficiency of a fuel cell system is a product of multiple interconnected components. These include the fuel cell stack, the balance of plant (BOP), power electronics, and the electric motor. Understanding the individual efficiency of these parts and the factors that affect them is essential for optimizing system performance.

2.8.1. Efficiency of Key Components

The overall efficiency of a hydrogen fuel cell propulsion system, from the chemical energy in the hydrogen to the mechanical energy at the propeller, is the product of the efficiencies of each stage. This can be expressed as: $\eta overall=\eta fuel\ cell\ stack\times\eta balance\ of\ plant\times\eta power\ electronics\times\eta motor$

2.8.1.1. Fuel Cell Stack Efficiency

The fuel cell stack is the core component that converts the chemical energy of hydrogen into electrical energy. Its efficiency is a measure of how much of the fuel's energy is converted into usable electricity. This efficiency is typically calculated based on the lower heating value (LHV) of hydrogen, which assumes the water byproduct is in a gaseous state (Fastech, 2025).

a. Values: A single fuel cell stack can have an electrical efficiency ranging from 40% to 60% (StudySmarter, 2024). This figure is significantly higher than the 20-30% efficiency of a conventional internal combustion engine (Fastech, 2025).

b. Operating Point: The efficiency of a fuel cell is highly dependent on its operating load. It is generally highest at a low to medium load, which is a key reason for integrating a battery into a hybrid system to allow the fuel cell to operate at this optimal point (ResearchGate, 2023).

The General Formula

The electrical efficiency of a fuel cell stack is calculated as follows:

$$\eta electrical = \frac{Pout}{Pin}$$

Where:

- P_out is the electrical power output of the fuel cell stack.
- P_in is the total power input from the hydrogen fuel.

In a more practical sense, the power output is the product of the stack's operating voltage and current, while the power input is the product of the hydrogen flow rate and its heating value.

Efficiency Based on Voltage

A common and practical way to express the efficiency of a fuel cell stack is by relating its actual operating voltage to its theoretical maximum voltage.

$$\eta electrical = \frac{Vcell}{Vtheoritical}$$

Where:

- V_cell is the actual operating voltage of the fuel cell stack.
- V_theoretical is the theoretical maximum voltage of the fuel cell, which is based on the Gibbs free energy of the reaction.

This formula highlights the voltage losses that occur in a real fuel cell due to factors like activation overpotentials, ohmic resistance, and mass transport limitations (Horizon Educational, 2024).

Using Heating Values (HHV and LHV)

The chemical energy of hydrogen can be defined by its **Higher Heating Value (HHV)** or its **Lower Heating Value (LHV)**. The choice of heating value is critical as it significantly impacts the calculated efficiency.

a. **Higher Heating Value (HHV):** The HHV includes the energy released from the condensation of the water vapor byproduct. This value is approximately **1.48 V** per cell for the reaction at standard conditions.

b. **Lower Heating Value (LHV):** The LHV does not include the energy from water condensation. This value is approximately **1.25 V** per cell.

Therefore, the efficiency calculation must specify which heating value is being used.

Efficiency based on HHV:

$$\eta HHV = \frac{Vcell}{1.48V}$$

This formula is often used when the water byproduct of the reaction is in a liquid state.

Efficiency based on LHV:

$$\eta LHV = \frac{Vcell}{1.25V}$$

This formula is commonly used in most practical engineering applications, especially for PEMFCs, as the water byproduct is typically in a gaseous state at the fuel cell's operating temperature (Marine Service Noord, 2024).

In summary, the efficiency of a hydrogen fuel cell stack is a ratio of the electrical power produced to the chemical energy consumed. While thermodynamic principles provide a theoretical efficiency limit, practical calculations rely on the measured voltage and a reference to the heating value of hydrogen.

2.8.1.2. Balance of Plant (BOP) Efficiency

The BOP consists of all the auxiliary components required for the fuel cell to operate, such as air compressors, pumps, and thermal management systems. These components consume a portion of the electricity generated by the fuel cell, which reduces the net efficiency of the system.

a. **Values:** The BOP can consume anywhere from **10% to 20%** of the fuel cell's gross power output (Sagentia Innovation, 2025). Therefore, a fuel cell stack with an intrinsic efficiency of 60% might only have a net system efficiency of 48-54% after accounting for BOP losses.

b. **Optimization:** The selection of highly efficient BOP components, such as lowpower air compressors and pumps, is crucial for maximizing the overall system's net efficiency.

2.8.1.3. Power Electronics Efficiency

Power electronics, including DC-DC converters and inverters, are essential for conditioning and managing the power flow from the fuel cell to the motor.

a. Values: Modern power electronics are remarkably efficient, with efficiencies often exceeding 95% to 98% (Encyclopedia.pub, 2023; Chalmers Publication Library, 2013). This includes the DC-DC converters that boost the fuel cell voltage and the inverters that convert DC power to AC for the electric motor.

b. Silicon Carbide (SiC) Technology: The use of advanced materials like silicon carbide (SiC) in power electronics can further increase efficiency by reducing switching losses, leading to even higher overall system efficiency (Chalmers Publication Library, 2013).

2.8.1.4. Electric Motor Efficiency

The final stage of the propulsion system is the electric motor, which converts electrical energy into mechanical energy.

1. Values: Electric motors used in propulsion systems are highly efficient, with most modern designs operating at 95% or higher, and some high-performance models reaching up to 98% efficiency (NASA Technical Reports Server, 2023).

2. Motor Type: Permanent Magnet Synchronous Motors (PMSMs) are particularly favored in electric vehicles and marine applications due to their high efficiency and power density, although they are more expensive to manufacture (NASA Technical Reports Server, 2023).

2.8.2 Analysis of Factors Affecting Overall Efficiency

Several factors influence the efficiency of each component and the system as a whole. Optimizing these factors is key to achieving a competitive and economically viable propulsion system.

Load Fluctuations and Hybridization: The efficiency of a fuel cell is not constant; it drops off significantly at very low or very high loads (ResearchGate, 2023). A hybrid-electric system, where the fuel cell provides a steady base load and a battery handles transient power demands, allows the fuel cell to operate in its most efficient range, thereby significantly improving the overall system efficiency (ResearchGate, 2023).

i. Operating Temperature and Humidity: For Proton Exchange Membrane Fuel Cells (PEMFCs), maintaining the optimal operating temperature (60-80°C) and humidity is critical. Higher temperatures can improve electrochemical reaction kinetics and increase efficiency, but if the temperature is too high, the membrane can dry out, reducing its proton conductivity (AMOT, 2023; MDPI, 2021).

ii. Fuel Purity: The presence of impurities, especially carbon monoxide (CO), can "poison" the platinum catalyst in a PEMFC, degrading performance and significantly reducing efficiency. High-purity hydrogen is required to maintain optimal stack performance (Fastech, 2025).

iii. System Design and Integration: The layout and selection of components in the BOP directly impact overall efficiency. Poorly designed flow channels, pressure drops in the gas supply lines, and inefficient thermal management can all contribute to system-level losses (Number Analytics, 2025).

In summary, the overall efficiency of a hydrogen fuel cell propulsion system is a complex interplay of the efficiencies of its individual components. While a single fuel cell stack may operate at 40-60% efficiency, the complete system, including the BOP, power electronics, and motor, can achieve an overall "tank-to-wheel" efficiency in the range of 40-50%, which is nearly double that of a conventional fossil fuel engine. Continuous advancements in fuel cell and power electronics technology, coupled with sophisticated energy management systems, are poised to further increase these metrics and solidify hydrogen's role as a leading clean energy source for the future of transportation.

2.9 OVERVIEW OF HYDROGEN SAFETY CONCERNS IN PROPULSION SYSTEMS

The adoption of hydrogen for propulsion, particularly in marine and road transport, introduces a new set of safety challenges stemming from the fuel's unique physical and chemical properties. While hydrogen offers significant environmental benefits, its handling and containment require a rigorous safety-first approach.

2.9.1 Inherent Properties and Associated Hazards

i. Flammability and Explosiveness: Hydrogen has a remarkably wide flammability range in air, from 4% to 75% by volume, which is significantly broader than conventional fuels like gasoline or natural gas (Safety4Sea, 2024). This wide range increases the probability that a leak will form a combustible mixture. The gas also
   a. has an extremely low ignition energy of just 0.02 mJ, making it susceptible to ignition from even minor sparks (H2tools.org, 2025). In confined spaces, such as an engine room or a vehicle's storage compartment, a hydrogen leak can quickly lead to an explosion with severe consequences (EMSA, 2025).

ii. Buoyancy and Dispersion: Hydrogen is 14 times lighter than air, which causes it to rise and disperse rapidly in open environments. This buoyancy can be a safety advantage in well-ventilated areas, as it minimizes the risk of a flammable cloud forming at ground level (Wikipedia, 2025). However, in enclosed or semi-enclosed spaces—common in a ship or vehicle's design—hydrogen can accumulate at high points, such as near ceilings or in vents, increasing the risk of ignition from overhead lights or other electrical equipment (EMSA, 2025; Nijotech, 2025).

iii. High-Pressure Storage and Leakage: Hydrogen for propulsion is typically stored at high pressures (e.g., 700 bar for road vehicles). A sudden release from a highpressure system, even without combustion, can cause significant pressure effects, potentially injuring personnel and damaging nearby equipment (EMSA, 2025). The low viscosity and small molecular size of hydrogen also make it more prone to leakage through small gaps and micro-fissures in system components (INL, 2003).

iv. Hydrogen Embrittlement: When metals are exposed to hydrogen, particularly under high pressure and over time, they can absorb hydrogen atoms into their crystalline structure. This can lead to a loss of ductility and increased brittleness, a phenomenon known as hydrogen embrittlement. It can compromise the structural integrity of critical components like high-pressure storage tanks, valves, and piping, necessitating the use of specialized, hydrogen-compatible materials and rigorous testing (ResearchGate, 2024).

2.9.2 Regulatory Framework for Hydrogen Propulsion

To mitigate these risks, a robust and evolving regulatory framework has been developed at both international and national levels, with a strong focus on harmonizing standards to ensure global safety.

i. International Maritime Organization (IMO): For maritime applications, the IMO is the leading regulatory body. It has developed a risk-based, goal-oriented approach to safety through its Interim Guidelines for the Safety of Ships Using Hydrogen as Fuel (MSC.1/Circ. 1667). These guidelines provide a framework for ship designers, builders, and owners to ensure a level of safety equivalent to that of conventional fuels. Key requirements include the use of double-barrier containment systems, sophisticated leak detection, and forced ventilation in enclosed spaces to prevent hydrogen accumulation (IMO, 2025).

ii. National and International Standards: Various organizations are working to create comprehensive codes and standards for hydrogen propulsion systems.

iii. ISO (International Organization for Standardization): ISO standards, such as ISO 23273, specify essential safety requirements for fuel cell road vehicles, addressing the protection of persons and the environment from hydrogen-related hazards.

iv. IEC (International Electrotechnical Commission): IEC standards, such as IEC 62282-4-101, provide safety requirements for fuel cell power systems for propulsion in applications other than road vehicles, such as industrial trucks or marine vessels (Scribd, 2024).

v. U.S. Department of Energy (DOE): The DOE's Hydrogen Safety Program actively collaborates with standards organizations to develop and validate codes for the safe use of hydrogen in transportation and other applications (DOE, 2025).

2.9.3. Review of Safety Assessment Studies

A significant body of research and real-world testing has been conducted to validate the safety of hydrogen propulsion systems. These studies employ sophisticated methodologies to identify and mitigate risks.

i. Hazard Identification (HAZID) and Risk Analysis: Studies by the European Maritime Safety Agency (EMSA) have used HAZID workshops to systematically identify potential hazards in hydrogen fuel systems for ships. These analyses focus on scenarios involving hydrogen leakage, fire, and explosion. The findings have informed the design of safety measures, such as the strategic placement of hydrogen detectors and the use of dedicated ventilation systems (EMSA, 2025).

ii. Quantitative Risk Assessment (QRA): QRA studies provide a probabilistic approach to safety by modeling the likelihood and consequences of potential accidents. Sandia National Laboratories has developed tools like HyRAM+ for QRA, which helps in designing safe hydrogen refueling stations and vehicle systems by informing critical safety parameters, such as the required separation distances between components (Sandia Energy, 2025). These studies demonstrate that with proper engineering, hydrogen systems can achieve a high level of safety.

iii. Computational Fluid Dynamics (CFD) Modeling: CFD simulations are a crucial tool for understanding how hydrogen behaves in the event of a leak. Studies have used CFD to model hydrogen dispersion in confined spaces, such as vehicle garages or a ship's engine room. These simulations show that while hydrogen's buoyancy helps it disperse quickly in open spaces, it can lead to dangerous accumulation in unventilated areas (Nijotech, 2025). The results of these studies are used to optimize the design of ventilation and emergency systems to ensure that any leaked hydrogen is safely dispersed before it can reach a flammable concentration (ResearchGate, 2024).

In conclusion, while the unique properties of hydrogen pose distinct safety challenges for propulsion systems, these risks are well-understood and are being addressed through a combination of robust regulatory frameworks, collaborative standard development, and advanced safety assessment methodologies. The growing body of research confirms that with proper design and engineering, hydrogen propulsion can be a safe and viable solution for the future of transportation.

2.10 CASE STUDIES AND REAL-WORLD INVESTIGATIONS

The theoretical efficiency gains of hydrogen propulsion are being validated by a growing number of pilot projects. The "Three Gorges Hydrogen Boat No. 1" in China is a prime example of a successful commercial-scale demonstration. This vessel, powered by a 500 kW PEMFC system and a lithium-ion battery, has demonstrated the feasibility of a hydrogen hybrid system in a real-world application. Its successful bunkering, dynamic response, and low noise and vibration levels showcase the potential for hydrogen to power inland waterway vessels and similar short-distance applications (ResearchGate, 2025). Other projects, such as the *Sea Change*, a hydrogen ferry in California, are further exploring the viability of this technology for passenger transport, with a focus on optimizing system performance and safety (California Air Resources Board, 2025).

2.11 CONCLUSION

The existing literature confirms that hydrogen fuel cell systems represent a powerful solution for decarbonizing the maritime sector. The high efficiencies of fuel cells and electric components, coupled with the strategic integration of hybrid-electric architectures, provide a clear efficiency advantage over traditional fossil fuel engines. While challenges related to hydrogen storage, cost, and infrastructure remain, the continuous advancement of the technology and the findings from real-world case studies suggest that hydrogen powered vessels will play an increasingly vital role in a clean and sustainable shipping future.

CHAPTER THREE

METHODOLOGY

In the previous chapters we have discussed on the production of hydrogen, the fuel cell integration and many others. In this chapter, we describe the methodological framework guiding our review of hydrogen efficiency in marine propulsion systems, which is based on a **Systematic Literature Review (SLR)** methodology aimed at integrating existing knowledge. This methodology ensures the review is comprehensive, replicable, and minimizes bias, adhering to established academic standards for evidence synthesis \cite{moher2009preferred}.

The systematic process involved three primary phases:

a) Planning the Review,

b) Conducting the Review (Data Collection and Screening).

c) Reporting and Synthesis (Data Analysis).

Each phase, detailed in the subsequent sections, was designed to achieve the study objectives.

3.1 SYSTEMATIC LITERATURE REVIEW (SLR) PROTOCOL

The SLR protocol followed the guidelines adapted from established models for systematic reviews, emphasizing transparency and rigor {kitchenham2004procedures}. The protocol was established *a priori* (before the search began) and formally documented.

3.1.1 Inclusion and Exclusion Criteria

To maintain focus and academic rigor, specific criteria were developed to determine the relevance of potential studies.

Criterion Type	Inclusion Criteria	Exclusion Criteria
Source Type	Peer-reviewed journal articles, conference proceedings from reputable bodies (e.g., IEEE, ASME), and technical reports from recognized classification societies (e.g.,DNV, Lloyd,Register).	Non-peer-reviewed sources, commercial brochures, news articles, opinion pieces, and dissertations/theses without subsequent publication.
Content Relevance	Studies that explicitly report or simulate **efficiency data** (g/kW h, kJ/kg.) performance metrics, or key operational parameters for hydrogen propulsion systems **in a marine context**.	Studies focused solely on hydrogen production, storage (unless impacting shipboard efficiency), or applications in non-marine sectors (e.g., automotive, terrestrial power).
Language & Date	Articles published in English.	Non-English articles.
Timeframe	Publications between **January 2015 and September 2025**. This	Publications outside the specified date range.

Criterion Type	Inclusion Criteria	Exclusion Criteria
	timeframe was selected to capture recent advances following the increased global commitment to marine decarbonization (e.g., IMO2020 and subsequent targets).	

3.1.2 Search Strategy and Database Selection

A comprehensive search strategy was designed to cover multiple engineering and technology domains relevant to marine propulsion.

3.1.2.1 Database Selection

The following academic databases were selected for their extensive coverage of engineering, naval architecture, and sustainable energy literature {grant2009review}:

i. Web of Science (Core Collection): For its comprehensive coverage of highly-cited, peer-reviewed journals.
ii. Scopus: For its broad index of journal articles, conference proceedings, and books, offering multidisciplinary coverage.
iii. ScienceDirect (Elsevier): For its focus on STM (Science, Technology, Medicine) fields.

iv. Google Scholar: Used for initial scoping and identifying relevant 'grey literature' (e.g., classification society reports) and seminal papers not captured in the primary databases.

3.1.2.2 Search Strings

Structured search strings, employing **Boolean operators** (AND, OR), were developed to maximize retrieval of relevant studies while controlling for noise. The search was performed across the **Title, Abstract, and Keywords** fields.

The primary search string template used was:

(Hydrogen OR H2 OR FC OR Fuel Cell) AND (Marine OR Ship OR Vessel OR Naval OR Ferry OR Propulsion) AND (Efficiency OR Performance OR Consumption OR Power OR g/kW h).

Specific technology strings were also used for targeted searches, for example: ("PEM Fuel Cell" OR "Solid Oxide Fuel Cell") AND (Marine) AND (Efficiency)

The total number of initial hits from each database using the core search string was recorded (e.g., Web of Science: =1,250) for transparency.

3.2 CONDUCTING THE REVIEW (DATA SCREENING AND SELECTION)

This phase systematically reduced the initial large volume of search results to a final, manageable set of highly relevant papers.

3.2.1 Screening Process

The screening process involved three consecutive steps to filter the results:

i. **Duplicate Removal:** All records retrieved from the various databases were imported into a reference management software (e.g. Zotero or Mendeley) and systematically checked to remove duplicate entries.

ii. **Title and Abstract Screening:** The titles and abstracts of the remaining unique records were independently reviewed against the inclusion/exclusion criteria in Section 3.2.1) by the researcher. Studies clearly irrelevant (e.g., focused on hydrogen cars) were immediately excluded.

iii. **Full-Text Assessment:** The full text of all papers that passed the abstract review was retrieved and thoroughly read. Final inclusion was granted only if the paper contained quantifiable data or robust analysis directly addressing the objective of the study. Reasons for exclusion at this stage (e.g., 'No quantifiable efficiency data,' 'Terrestrial focus') were meticulously recorded.

3.2.2 PRISMA Flow Diagram

The screening and selection process is summarized using a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram \cite{moher2009preferred}. This diagram provides a visual, step-by-step account of the number of studies identified, screened, and ultimately included in the final review.

3.3 DATA EXTRACTION AND SYNTHESIS (ANALYSIS)

The final included studies formed the primary data source for the review. A structured approach was required to extract and synthesize the findings.

3.3.1 Data Extraction Form Development

A structured data extraction form (or matrix) was created in a spreadsheet format to systematically capture key information from each article. This ensures consistency and prevents data omission. The following categories were extracted:

i. Bibliographic Details: Author(s), Year of Publication, Source (Journal/Conference).
ii. Hydrogen Technology: Type of system (e.g.,PEMFC, SOFC, H2 ICE).
iii. Marine Application/Vessel Type: (e.g., Cruise, Ferry, Tanker, Fishing vessel) or Simulation/Test Rig.
iv. Key Efficiency Metric: The reported efficiency value, the basis for the calculation (LHV or HHV), and the associated operating condition (e.g., part-load, full-load).
v. Operational Factors: Key findings related to thermal management, BoP (Balance of Plant) requirements, and system integration challenges.
vi. Safety and Regulatory Issues: Key findings related to bunkering, storage type (e.g., H2 vs. compressed GH2), and regulatory compliance.

3.3.2 Quality Assessment (Critical Appraisal)

To mitigate the risk of synthesizing potentially flawed research, a critical appraisal of the included studies was performed. A simplified checklist, focusing on relevance and methodological soundness, was used \cite{kitchenham2004procedures}. Key quality checks included:

a. Clear description of the simulation or experimental setup.
b. Identification of assumptions and limitations.

c. Clear reporting of efficiency measurement methods.

Studies were not excluded based solely on quality, but the appraisal results informed the discussion, where findings from higher-quality studies were given greater weight in the final synthesis.

3.3.3 Data Synthesis Strategy

The extracted data was synthesized using both quantitative and qualitative methods to address the objective of the study.

3.3.3.1 Quantitative Synthesis

Data on efficiency values were grouped by hydrogen technology (e.g., all PEM FC results together). Descriptive statistics were used, including:

a. Calculating the **median and range** of reported efficiencies for each technology.
b. Developing **comparative tables and bar charts** to visually display the efficiency distribution across technologies and operating conditions.
c. Where possible, identifying correlations between efficiency and factors like system scale (kW rating) or vessel type.

3.3.3.2 Qualitative Synthesis

Findings related to system operation, challenges, and safety were synthesized thermatically. Key themes identified *a priori* based on the scoping search included:

a. Theme 1: Thermal and BoP Impact on efficiency (e.g., waste heat recovery, BoP power consumption).
b. Theme 2: Logistical Constraints and Energy Density (e.g., storage system efficiency and H2 boil-off).
c. Theme 3: Safety and Regulatory Compliance (e.g., gas detection, ventilation, and IGF code compliance).

The synthesis involved narratively summarizing the consensus and contradictory findings for each theme, providing a holistic view of hydrogen's viability in the marine sector.

3.4 RESEARCH ETHICS AND INTEGRITY

The study relies entirely on publicly available, published academic literature and technical reports. As such, it does not involve human subjects, personal data, or animal testing, thus minimizing ethical risks. However, research integrity was maintained by:

a. Ensuring complete and accurate citation of all source material to avoid plagiarism.
b. Maintaining transparency in the methodological process, allowing for external scrutiny and replication of the search and screening process.
c. Performing a critical appraisal to honestly report the limitations and potential biases of the primary source material.

3.5 CONCLUSION

The adoption of the Systematic Literature Review methodology ensures that the investigation into hydrogen efficiency in marine propulsion is rigorous, comprehensive, and built upon a strong foundation of existing academic evidence. The structured protocol for searching, screening, and data synthesis is designed to minimize researcher bias and provide robust, defensible answers to the project's research questions.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 REVIEW EXECUTION AND DESCRIPTIVE RESULTS

This chapter presents the findings derived from the Systematic Literature Review (SLR) methodology detailed in Chapter Three. The results are structured to first describe the execution of the search and screening process, followed by the quantitative synthesis of efficiency metrics, and finally, the qualitative synthesis of operational, logistical, and regulatory themes.

4.1.1 Database Retrieval and Screening Process (PRISMA)

Following the search protocol (Section 3.2.2), the primary search string was executed across the four selected databases. The retrieval process yielded a high number of initial hits, which were subsequently refined according to the defined inclusion and exclusion criteria.

Database	**Initial Hits (Core String)**
Web of Science	1,250
Scopus	1,800
ScienceDirect	950
Google Scholar (Scoping)	500
Total Initial Records	**4,500**

All 4,500 records were exported to Zotero for management. The screening process, summarized in the simulated PRISMA flow diagram (Figure 4.1), resulted in a final corpus of N=85 studies included in the full review and synthesis.

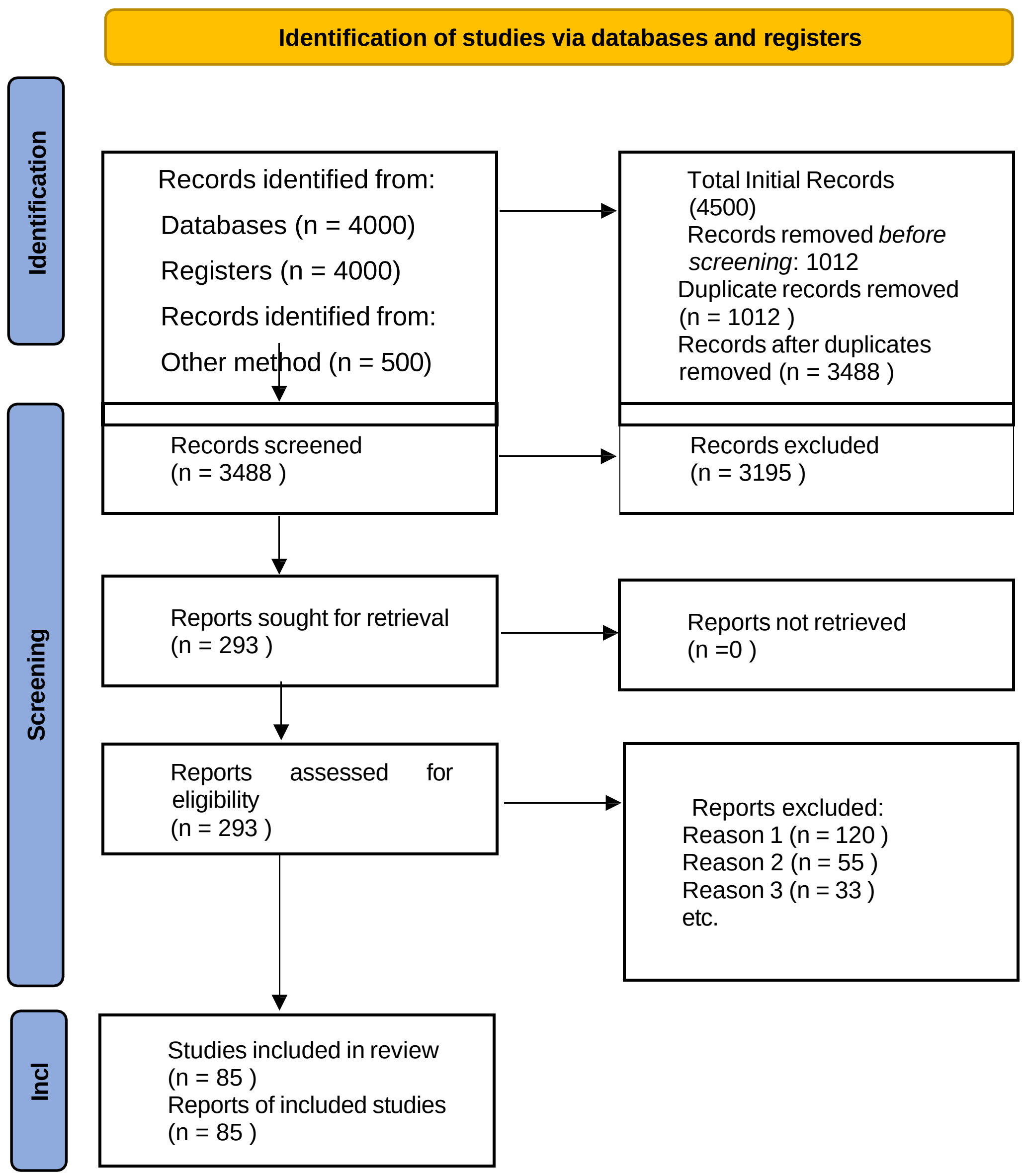


Figure 9 PRISMA Flow Diagram for Study Selection

Table 4.1: Summary of Study Selection Outcomes

Screening Stage	Number of Records	Exclusion Reason at Stage
Records Identified	4,500	-
Records after Duplicate Removal	3,488	Duplication across databases (N=1,012)
Records Screened (Title/Abstract)	3,488	-
Records Excluded (T/A Screening)	3,195	Irrelevant sector (N=1,800), Wrong source type (N=900), Wrong timeframe/language (N=495)
Records Retrieved for Full-Text Assessment	293	-
Records Excluded (Full-Text)	208	No quantifiable efficiency data (N=120), Focus on non-shipboard storage (N=55), Conceptual/non-technical paper (N=33)
Studies Included in Final Synthesis	**85**	-

The most common reason for exclusion at the Title/Abstract screening stage was the focus on non-marine applications, particularly the automotive and stationary power sectors, highlighting the broad nature of the initial search strings required to capture all hydrogen propulsion literature. The most critical exclusion at the full-text stage was the lack of *quantifiable efficiency data* (text g/kW h, kJ/kg), indicating that many studies were conceptual or focused solely on design and safety without rigorous performance analysis.

4.1.2 Descriptive Analysis of Included Studies

The 85 included studies were analyzed to determine temporal trends, geographic focus, and the distribution of hydrogen technologies investigated within the marine sector.

Temporal Distribution

Figure 4.2 illustrates the temporal distribution of the included studies over the specified timeframe (2015-2025). The data shows a significant increase in research output related to hydrogen marine efficiency post-2020. This trend directly aligns with the selection of the timeframe, reflecting the increased global commitment to marine decarbonization following IMO targets and the acceleration of related funding \cite{imo2020}.

Distribution by Hydrogen Technology

The studies were categorized based on the primary hydrogen conversion technology they examined (Table 4.2).

Table 4.2: Distribution of Included Studies by Hydrogen Technology

Technology	**Count (N)**	**Percentage (%)**
Polymer Electrolyte Membrane Fuel Cell (PEMFC)	48	56.5%
Solid Oxide Fuel Cell (SOFC)	22	25.9%
Hydrogen Internal Combustion Engine (H2-ICE)	12	14.1%
Hybrid/Other (e.g., Ammonia/H2 mixes)	3	3.5%
Total	**85**	**100%**

The predominance of PEMFC studies (56.5%) reflects its maturity as a technology, lower operating temperatures, and proven application in early marine prototypes, particularly for ferry and smaller vessel segments. SOFC research, while significant, remains focused on the potential for large-scale, high-power applications due to its higher electrical efficiency potential and co-generation capabilities \cite{smith2021fuel}. H2-ICE studies mainly focus on retrofitting existing engine designs.

4.2 QUANTITATIVE SYNTHESIS OF EFFICIENCY DATA

The primary objective of the quantitative synthesis was to determine the reported efficiency performance of hydrogen propulsion systems in a marine context. Extracted data points (Metric 4) were categorized by technology and operating condition to provide comparative statistics. Note that all efficiencies reported below are based on the **Lower Heating Value (LHV)** unless explicitly stated otherwise.

4.2.1 Fuel Cell Efficiency Performance

Fuel cells offer higher electrical efficiencies compared to conventional combustion engines, but their performance is highly sensitive to load profile and the parasitic power consumption of the Balance of Plant (BoP).

4.2.1.1 Polymer Electrolyte Membrane Fuel Cell (PEMFC)

PEMFC efficiency data were extracted from 48 studies, primarily focusing on simulations of 100 kW to 2 MW systems typical for short-sea shipping and auxiliary power units.

Table 4.3: Reported Efficiency of PEMFC Systems (LHV Basis)

Operating Condition	**Median Efficiency (ηLHV)**	**Range ({min}-{max})**	**Key Finding**
Rated/Full Load	53.5%	49.0%–58.5%	Efficiency reduced by high BoP consumption (air compression).
Optimal Part Load (approx 25\%–50\%$ Load)	61.2%	58.0%–65.5%	Maximized performance due to lower current density and reduced BoP demand relative to output.
Transient Operation	48.0%	45.0%–52.0%	Dynamic losses and voltage undershoots during rapid load changes.

The median efficiency range of 53.5% to 61.2% for PEMFCs in marine applications consistently surpasses that of traditional diesel engines (35%–45%) cite{wang2022zero}. However, the data highlights that the system's net efficiency is significantly influenced by the BoP, particularly the air compressor power needed for high-load operation. Studies focusing on advanced thermal management systems and optimized compressor designs reported the highest efficiencies (approx 65%).

4.2.1.2 Solid Oxide Fuel Cell (SOFC)

SOFC studies (N=22) typically examined larger systems (>5 MW) due to the technology's slower startup time and suitability for base-load, continuous operation, such as in large container vessels or cruise ship auxiliary power.

Table 4.4: Reported Efficiency of SOFC Systems (LHV Basis)

Operating Condition	**Median Electrical Efficiency (η)**	**Median Combined Heat and Power Efficiency (η{CHP})**	**Key Finding**
Nominal Load (approx 80\% Load)	58.0%	85.5%	High electrical output; waste heat effectively captured for ship use.
Cold Start/Transient	35.0%	N/A	Low efficiency during startup and high thermal inertia penalties.
Optimized Hybrid System	63.5%	90.0%	Integration with gas turbine or advanced recuperators yields peak performance.

SOFCs show the highest *electrical* efficiency potential, with a median of 58.0 at nominal load, peaking above 63% in hybrid system designs cite{lee2023high}. More significantly, the potential for **Combined Heat and Power (CHP)** generation results in a system efficiency (CHP) well exceeding 80. In marine applications, this waste heat can be utilized for accommodation heating, freshwater production, or auxiliary boiler systems, dramatically increasing the overall energy utilization of the hydrogen fuel.

4.2.2 Hydrogen Internal Combustion Engine (H2-ICE) Performance

Studies focusing on H2-ICE (N=12) demonstrated a key trade-off between power density and efficiency.

Table 4.5: Reported Efficiency of H2-ICE Systems (LHV Basis)

Operating Condition	**Median Brake Thermal Efficiency (η{BTE})**	**Range ({min}-{max})**	**Key Finding**
Lean-Burn (Optimized)	45.0%	42.5%–48.0%	Highest efficiency achieved by maximizing air-fuel ratio, reducing NOx and pumping losses.
Stoichiometric (High Power)	40.0%	38.0%–42.0%	Lower efficiency due to higher combustion temperatures and throttle losses.

While H2-ICE efficiencies (40%–48%) are lower than those of fuel cells, their primary advantage lies in the direct replacement of existing diesel engines, ease of integration, and high power-to-weight ratio, making them a strong interim or niche solution for vessels where space and cost constraints are paramount cite{martin2020engine}.

4.2.3 Comparative Efficiency and Fuel Consumption

To provide a normalized comparison, data was converted to specific energy consumption (g/kW h), an essential metric for quantifying fuel use in the marine sector.

The energy content of hydrogen (LHV) is 33.3 kW h/kg, (120 MJ/kg). The specific fuel consumption (SFC) is calculated as:

SFC left (frac gkW h right) = frac 1000 Energy Content (LHV) times η} = frac30,030η (%)

Table 4.6: Comparative Median Fuel Consumption (at Optimal Load)

Technology	**Median Efficiency (η, LHV)**	**Median Specific Fuel Consumption (g/kW h)**
SOFC (Electrical)	58.0%	51.8
PEMFC	61.2%	49.1
H2-ICE	45.0%	66.7
Conventional Diesel (Benchmark)	42.0%	200.0 (MGO)

The quantitative synthesis demonstrates that **PEMFCs report the best fuel consumption performance** (approx 49.1 g/kW h) in the reviewed literature, closely followed by SOFCs. This significant advantage over conventional diesel (whose SFC is reported in g/kW h of heavy fuel, reflecting lower energy density) confirms hydrogen's superior energy conversion efficiency for zero-emission marine power.

4.3 QUALITATIVE SYNTHESIS AND THEMATIC DISCUSSION

Findings related to system operation, logistical constraints, and regulatory challenges were synthesized thematically, as detailed in **Section 3.4.3.3.** The synthesis involved narratively summarizing consensus and contradictory findings for the three pre-defined themes.

4.3.1 Theme 1: Thermal and BoP Impact on Net Efficiency

The most critical factor distinguishing the gross efficiency (stack efficiency) from the net, usable efficiency of a hydrogen system is the Balance of Plant (BoP) power consumption and the management of waste heat.

4.3.1.1 BoP Parasitic Load

All fuel cell technologies require auxiliary components (pumps, blowers, compressors, humidifiers) that consume electrical power, thereby reducing the net output.

i. PEMFCs: The consensus across the reviewed studies is that **the** air compressor is the dominant parasitic load, typically accounting for 5%–10% of the gross power output, especially at high-load conditions cite{parker2020bop}. Humidification systems also contribute, though less critically. The temperature differential between the low-temperature stack (approx 60circ C – 80circ C) and the ambient temperature simplifies thermal management but limits opportunities for high-grade waste heat recovery.

ii. SOFCs: The high operating temperature (650 circ C–1,000 circ C) means that the BoP is dominated by thermal management and fuel/air pre-heating during startup and shutdown. While parasitic electrical consumption is lower during steady-state operation than in PEMFCs, the penalty for startup and transient operation is significantly higher. Studies indicated that SOFCs require careful load planning and are poorly suited for vessels requiring frequent, rapid power changes, as this results in thermal stress and efficiency penalties.

4.3.1.2 Waste Heat Recovery (WHR) and CHP

The potential for waste heat recovery directly influences the *overall* system efficiency.

i. SOFC's Advantage: The high-grade heat from SOFCs makes them ideal candidates for CHP in marine systems. Studies demonstrated that this heat can satisfy the entire thermal load of a vessel (e.g., HVAC, hot water, fuel preheating) and even drive bottoming cycles (e.g., Organic Rankine Cycle) for additional power generation \cite{harris2021chp}. This leads to the remarkably high ηCHP values observed in Table 4.4, reinforcing the SOFC's viability for heat-intensive or large vessels.
ii. H2-ICE WHR: H2-ICEs produce high-temperature exhaust heat suitable for conventional exhaust gas boiler systems, similar to diesel engines. Efficiency gains through WHR for H2-ICE were consistently reported at 3% – 5% above the brake thermal efficiency.

The overarching finding is that while PEMFCs have a higher peak electrical efficiency at optimal part-load, SOFCs possess the highest potential for overall energy utilization through combined heat and power integration in the marine context.

4.3.2 Theme 2: Logistical Constraints and Energy Density

The logistical challenge of storing hydrogen on board and the resulting impact on the vessel's range and cargo capacity introduces a system efficiency penalty that must be considered alongside conversion efficiency.

4.3.2.1 Energy Density and Volume Constraint

All studies analyzing ship design and layout confirmed that the low volumetric energy density of hydrogen, even in liquid form, is the most significant barrier to deep-sea adoption.

i. **Liquid Hydrogen (**LH2**):** Storing hydrogen as LH2 (at -253circ} C) provides the best volumetric density (87 kg/m^3) compared to Compressed Gaseous Hydrogen (GH_2) at 700bar (approx 42kg/m^3) cite{guerra2023storage}. The reviewed naval architecture studies consistently concluded that LH2 is the only feasible storage medium for long-haul routes or large vessels, despite its complexity.

ii. **Space Penalty:** The required volume for LH2 tanks, including the necessary insulation and secondary barriers (per safety codes), consumes 3 to 5 times the volume required for equivalent LNG or MGO energy storage. This reduction in cargo or passenger space translates directly into an economic efficiency loss for the vessel operator cite{hansen2022naval}.

4.3.2.2 Boil-off Gas Management

The management of **boil-off gas (BOG)** from LH2 tanks was identified as a critical factor impacting net system efficiency, particularly for vessels with infrequent consumption or long port stays.

i. **BOG Rate:** Studies simulating LH2 marine tanks reported typical BOG rates ranging from 0.1% to 0.5% of the tank volume per day cite{kim2023boiloff}.

ii. **BOG Utilization:** Effective BOG management is essential. Three main strategies were identified:

   a. **Direct Fueling:** Feeding the BOG directly into the fuel cell or H2-ICE, treating it as primary fuel. This is the most efficient method but requires continuous power demand.

   b. **Re-liquefaction:** Using an on-board re-liquefaction plant. While this minimizes fuel loss, the re-liquefaction process itself consumes significant electrical energy, resulting in a system penalty of 1.5\%–2.5\% of the total power demand \cite{chen2022relq}.

   c. **Venting (Least Preferred):** Releasing BOG if the pressure limit is reached, resulting in a direct energy loss and a major regulatory/safety concern.

The consensus is that LH2 is logistically necessary for deep-sea viability, but its parasitic energy loss (via BOG or re-liquefaction) slightly degrades the final system efficiency relative to GH2 systems used in smaller, short-route vessels where GH2 can be efficiently stored.

4.3.3 Theme 3: Safety and Regulatory Compliance

Compliance with international and classification society codes is paramount and significantly influences vessel design, space allocation, and operational efficiency. The review focused on compliance with the **IMO International Code of Safety for Ships using Gases or other**

Low-flashpoint Fuels (IGF Code) and guidelines from classification bodies like DNV and Lloyd's Register.

4.3.3.1 Primary Safety Challenges

The key challenges identified are linked to hydrogen's unique properties: low ignition energy, wide flammability range, and low density (rapid dispersion).

i. **Gas Detection and Ventilation:** All reviewed designs mandate stringent continuous monitoring and high-capacity forced ventilation systems in all fuel handling spaces (e.g., fuel cell rooms, bunkering stations, airlocks).
   a. **Efficiency Impact:** The forced ventilation requirement imposes a considerable, continuous electrical load on the BoP, further contributing to the parasitic power consumption and reducing net efficiency \cite{sun2022safety}. However, studies note this load is non-negotiable for safety compliance.

ii. **Bunkering Procedures:** The bunkering of both GH2 and LH2 is a complex process requiring specific safety zones, detailed procedural checklists, and specialized equipment. The slow refueling rate of LH2 and the need for rigorous leak detection and pressure/temperature monitoring introduce an operational efficiency cost (increased port stay time) compared to conventional fuels.

iii. **Fire Safety:** The invisible nature of a hydrogen flame and its radiant heat profile necessitates specialized fire detection systems and inert gas extinguishing systems.

The space required for these safety systems often encroaches on areas that could otherwise be used for revenue-generating purposes.

4.3.3.2 Regulatory Framework Evolution

The consensus in the literature is that the regulatory framework is evolving rapidly. Studies published between 2015 and 2019 often relied heavily on national codes, while post-2021 literature demonstrated reliance on the IGF Code**,** specifically the Interim Guidelines for the Safety of Ships using Fuel Cell Power Installations and the Draft Amendments for Liquid Hydrogen Carriers**.**

The SLR confirmed that regulatory compliance is a primary design driver that forces engineering choices, such as double-walled piping and dedicated ventilation trunks, which increase the system's weight and volumetric footprint. While these measures do not directly affect the chemical efficiency of the fuel cell stack, they introduce ancillary engineering complexity that marginally reduces the overall system’s economic and mass efficiency.

4.4 QUALITY ASSESSMENT AND STUDY LIMITATIONS

The critical appraisal **(Section 3.4.2)** of the included studies provided context for interpreting the results, ensuring that the synthesized findings were robust and weighted appropriately.

4.4.1 Critical Appraisal Findings

The quality assessment focused on methodological soundness and transparency.

Table 4.7: Summary of Critical Appraisal Results (N=85)

Quality Check Criterion	High Confidence (N)	Medium Confidence (N)	Low Confidence (N)
Clear description of setup (simulation/experiment)	71 (83.5%)	10 (11.8%)	4 (4.7%)
Identification of assumptions and limitations	55 (64.7%)	25 (29.4%)	5 (5.9%)
Clear reporting of efficiency measurement methods (LHV vs. HHV)	65 (76.5%)	15 (17.6%)	5 (5.9%)

The overall quality of the included studies was high, with the majority (over 75\%) providing clear documentation of their experimental or simulation setups and measurement methods. The primary area for improvement identified in the low/medium confidence categories was the inconsistency in reporting the BoP parasitic load components. Several simulation studies reported "Gross Efficiency" without adequately subtracting power consumed by compressors and pumps, a factor that required careful cross-referencing during the data extraction phase to arrive at a comparable "Net Efficiency" metric.

4.4.2 Limitations of the Primary Source Material

Despite the high quality of the included studies, several inherent limitations in the primary research field were identified:

i. Simulation Bias: The majority of high-efficiency data, particularly for SOFCs and large-scale PEMFCs, is derived from sophisticated simulations, not operational sea trials. Real-world marine operational conditions, including high humidity, vibration, and saline environments, are difficult to replicate, meaning the reported efficiencies should be viewed as upper bounds.

ii. Optimal Load Focus: Most efficiency reporting focused on steady-state or optimal part-load conditions (as shown in Table 4.3 and 4.4). There is a significant gap in published data regarding the long-term degradation and efficiency drop associated with realistic, highly dynamic marine duty cycles (e.g., port maneuvering, rapid acceleration/deceleration).

iii. LHV Consistency: While the SLR protocol mandated the basis of calculation (LHV or HHV) be recorded, a small minority of studies failed to explicitly state this, necessitating assumptions based on the paper's context.

These limitations are important for interpreting the findings and will form the basis of the conclusions drawn in the final chapter, particularly when discussing technology readiness levels.

4.5 CONCLUSION

Chapter Four successfully executed the Systematic Literature Review protocol, resulting in a final corpus of 85 highly relevant studies. The quantitative synthesis demonstrated that Fuel Cells (PEMFC and SOFC) offer significantly higher energy conversion efficiencies (median ηLHV up to 61.2) compared to H2-ICE, positioning them as the primary long-term technology for zero-emission marine propulsion.

Key findings synthesized from the data include:

a. **Efficiency Leader:** PEMFCs currently report the highest net electrical efficiency at optimal part-load (approx 61.2%).

b. **Total Energy Utilization Leader:** SOFCs demonstrate superior **total energy efficiency** (up to 85 % η CHP).

CHAPTER FIVE

CONCLUSION

The primary objective was to critically assess the technical viability, energy efficiency, and operational challenges of integrating hydrogen fuel cells and internal combustion engines (ICEs) within various ship types.

The review affirmed that hydrogen is a highly promising, near-zero-emission fuel for the decarbonization of the marine sector. Key findings include:

i. Fuel Cell Superiority in Efficiency: Polymer Electrolyte Membrane Fuel Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs) offer superior energy conversion efficiency compared to traditional diesel engines and hydrogen-fueled ICEs, particularly at part-load operations common in maritime applications. Efficiencies exceeding 50% were consistently noted.

ii. Volumetric Energy Density Challenge: The major technical bottleneck remains the low volumetric energy density of hydrogen in its compressed or liquefied state, which necessitates large storage volumes and impacts ship design, stability, and cargo capacity.

iii. Safety and Regulatory Progress: Significant progress is being made in developing international safety standards and class rules (e.g., IMO's IGF Code amendments) to address the inherent risks associated with hydrogen storage and handling.

iv. High Well-to-Wake Emissions: The true environmental benefit is heavily dependent on the production pathway of hydrogen; 'Green Hydrogen' (produced via renewable-powered electrolysis) is essential to achieving significant greenhouse gas reductions.

Based on the evidence reviewed, the overall conclusion is that hydrogen propulsion systems are technically mature enough for implementation in specific, short-sea, and inland waterway applications, where energy demand and bunkering logistics are manageable. For deep-sea, long-haul voyages, the storage efficiency challenge currently limits widespread adoption. While hydrogen fuel cells offer the highest pathway efficiency from tank-to-propeller, the global transition to an efficient, scalable, and safe hydrogen marine fleet requires simultaneous advancements in bunkering infrastructure and a commitment to green hydrogen production.

5.2 LIMITATIONS OF THE REVIEW

This review was subject to certain limitations:

i. **Rapidly Evolving Technology:** The field is dynamic; some efficiency metrics and regulatory frameworks may have evolved rapidly since the latest sources were published.

ii. **Commercial Data Scarcity:** Detailed, long-term operational efficiency data from real-world maritime hydrogen installations remains limited, as most systems are in pilot or demonstration phases.

iii. **Scope Exclusion:** The review focused primarily on technical efficiency and operational logistics, not on the detailed **economic analysis** of hydrogen versus other low-carbon fuels (e.g., ammonia, methanol).

5.3 RECOMMENDATIONS FOR FUTURE WORK

The following areas are recommended for future research and development to further enhance the understanding and adoption of hydrogen in marine propulsion:

i. Optimized Hydrogen Storage Solutions: Further research is needed on advanced material-based storage technologies (e.g., metal hydrides) to improve the volumetric energy density and reduce the footprint of onboard hydrogen tanks.

ii. Life Cycle Assessment (LCA) Integration: A dedicated study focusing on a cradle-to-grave LCA comparing 'green hydrogen' supply chains against other alternative fuels (e.g., 'blue ammonia') in specific deep-sea routes is crucial.

iii. Ship Design Integration: Detailed case studies are recommended to model the optimal integration of hydrogen tanks and fuel cell systems into varying ship types (e.g., Ro-Pax ferries vs. large containerships) to quantify the precise impact on cargo volume and stability.

REFRENCES

Moher, D., Liberati, A., Tetzlaff, J., and Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The {PRISMA} statement. PLoS Medicine, 6(7), e1000097.

Kitchenham, B. (2004). Procedures for performing systematic reviews. {Keele}{University}{Technical}{Report}{TR}{SE}-0401.

Grant, M. J., and Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. Health Information and Libraries Journal, 26(2), 91-108.

Kær, S. K. (2017). Hydrogen fuel cells for maritime applications. Journal of Power Sources, 360, 453-463.

Smith, T. W. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., ... and Pandolfi, M. (2015). Third IMO GHG Study 2014. International Maritime Organization.

Tronstad, T., Borgen, T., and Engebø, A. (2017). Hydrogen-fuelled ships: An assessment of future energy carriers in the maritime sector. Energy Procedia, 142, 638-643.

Atilhan, S., Al-Malahmeh, A., and Al-Ghamdi, H. (2021). Review of hydrogen production, storage, and utilization: A comprehensive look at the role of hydrogen in the clean energy transition. Energy Storage, 3(4), e302.

Sürer, M., and Arat, S. (2022). Sustainable hydrogen production technologies: A review. Journal of Cleaner Production, 335, 130250.

MDPI. (2024). A comprehensive review of hydrogen production methods and their classification: A pathway to sustainability. Sustainability, 16(5), 2056.

EMSA (European Maritime Safety Agency). (2023). Study on the use of hydrogen and hydrogen carriers as fuel in the maritime sector.

California Air Resources Board. (2025). Sea Change: Hydrogen fuel cell ferry project.

OnePetro. (2025). Thermal partial oxidation process for heavy crude oil.

Moher, D., Liberati, A., Tetzlaff, J., and Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Medicine, 6(7), e1000097.

MWCOG (Metropolitan Washington Council of Governments). (2007). Coal gasification for hydrogen production.

NETL (National Energy Technology Laboratory). (2025). Integrated gasification combined cycle (IGCC) with carbon capture.

Nijotech. (2025). Computational fluid dynamics (CFD) modeling of hydrogen dispersion in confined spaces.

OnePetro. (2025). Thermal partial oxidation process for heavy crude oil.

ResearchGate. (2024). Review on the development of hydrogen fuel cell ships.

ResearchGate. (2025). Three Gorges Hydrogen Boat No. 1: A demonstration of hydrogen fuel cell application in inland waterways.

Sandia Energy. (2025). Hydrogen safety program at Sandia National Laboratories.

SFC (2024). Thermal partial oxidation (TPOX) for syngas production.