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Life cycle assessment and life cycle cost assessment of offshore wind-based hydrogen production: in the case of Saldanha Bay (South Africa)

Thandeka Nonceba Tembe

LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST ASSESSMENT OF OFFSHORE WIND-BASED HYDROGEN PRODUCTION: IN THE CASE OF SALDANHA BAY (SOUTH AFRICA)

THANDEKA TEMBE

A dissertation submitted to the World Maritime University in partial fulfillment of the requirements for the award of the degree of Master of Science in Maritime Affairs

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my personal views and are not necessarily endorsed by the University.

Signature: Pembe

Date: **October 2023**

Supervised by: **Prof. Alessandro Schöborn**

Supervisor’s affiliation: Dr. Tuan Dong

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Abstract

Title of Dissertation: Life cycle assessment and life cycle cost assessment of offshore wind-based hydrogen production in Saldanha Bay (South Africa).

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Maritime transportation faces uncertainties as it transitions from fossil fuel reliance to greener options, like green hydrogen, to adhere to strict environmental regulations and the decarbonization pathway. The study's focus was a comparative analysis, encompassing Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA), of three marine propulsion systems: marine diesel oil, green hydrogen with internal engine combustion, and green hydrogen used in solid oxide fuel cells, evaluating their environmental impacts and economic performances.

A two-stroke chemical tanker served as a 30-year case study to explore the economic and environmental implications. Environmental impacts were assessed based on both IMO and IPCC frameworks. The study revealed that Saldanha Bay, with an annual cumulative wind power yield of 20 million kWh, is an ideal location for hydrogen production.

Results showed that MDO emitted more greenhouse gases than hydrogen, with differences evident in both Well-to-Tank (0.58 kgCO_2eq./kWh) and Tank-to-Wake (0.00012 kgCO_2eq./kWh) system boundaries. Despite carbon credits, MDO remained more cost-effective compared to the other propulsion systems, including green hydrogen used in solid oxide fuel cells and internal combustion engines. However, fuel cell materials contributed 0.356 kgCO_2eq./kWh emissions and incurred significant costs.

Furthermore, electricity production via wind proved cost-effective, but high hydrogen production costs resulted from electrolysis and the early stage of the product life cycle.

KEYWORDS: Life cycle assessment, Life cycle cost assessment, Green hydrogen, Solid oxide fuel cells, and marine diesel oil.

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List of Abbreviations

Abbreviation	**Full Form**
BC	Black Carbon
GHG	Greenhouse Gas
IMO	International Maritime Organization
H_2	Hydrogen
MDO	Marine Diesel Oil
HFO	Heavy Fuel Oil
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
WTT	Well To Tank
TTW	Tank To Well
GH_2	Green Hydrogen
LH_2	Liquid Hydrogen
CH_2	Compressed Hydrogen
NOx	Nitrogen Oxide
CH_4	Methane
SOx	Sulphur Oxides
CO	Carbon Monoxide
CO_2	Carbon Dioxide
LHV	Low Heat Value
KWH	Kilowatt Hour
FC	Fuel Consumption
SOFC	Solid Oxide Fuel Cells
ICE	Internal Combustion Engine
PEM	Proton Exchange Membrane
MC	Molten Carbonate
AFC	Alkaline Fuel Cell
LCCA	Life Cycle Cost Assessment
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory

LCIA	Life Cycle Impact Assessment
IPCC	Intergovernmental Panel for Climate Change
GMP	Good Manufacturing Practices
Mt CO_2 eq	Metric Tons of Carbon Dioxide Equivalent
SOE	Steam Methane Reforming
FU	Functional Unit
PBP	Payback Period
NPV	Net Present Value
IRR	Internal Rate of Return
GWP100	Global Warming Potential
MDE	Marine Diesel Engine
SOE	Solid Oxide Electrolyzer
OWS	Offshore Wind System
SMR	Steam Methane Reforming
RE	Renewable Energy
SIE	Steam Ignition Engine
RSA	Republic of South Africa
CCC	Carbon Credit Cost
AC	Annual Cost

Chapter 1: Introduction

Background of the Study

Introduction

Global trade equates to eighty percent through maritime transportation, which constitutes the core form of trade. However, in the past years, maritime transport has increased its trade due to globalization and the high supply and demand of resources. This means that more use of fossil fuels has increased the emissions of greenhouse gases. Thus far, the maritime industry emits approximately one billion tons of GHG from burning fossil fuel (IMO, 2023; IRENA, 2022) compared to 1080 million tons in 2018 (IMO, 2020). Even though IMO (2020) predicted that by the year 2050, maritime transportation will have emitted 20 to 250 percent of greenhouse gases as opposed to 2008, this prediction can potentially be enormously more significant to how the industry operates through business as usual. The increase in greenhouse gas emission is generally associated with the operation phase of the vessel, which is on fuel consumption (IMO, 2020).

The fuel consumption of the marine fleet is dominated by heavy fuel oil (HFO), followed by MDO (MDO) at 16 percent, liquefied natural gas (LNG) at 4 percent, and methanol, H_2, ammonia, and other alternative fuels at 0,1 percent as a marine fuel source (IRENA, 2021) as cited in (Guven & Kayalica, 2023). The 0,1 percentage is to be further explored as part of the decarbonization pathway to 2050 (Xing *et al.*, 2021); the pathway is to attempt to reduce the global temperature to 1.5°C as part of the United Nations Framework Climate Change Convention as part of the Paris Agreement. Therefore, the IMO developed a measure to mitigate GHG emissions by 2050 using medium to long-term market base measures for both technical and operations. Hence, the introduction of alternative fuels to reduce the global temperature, even though the sector contributes only 3 percent of GHG. According to IRENA (2023), GH_2 will amount to a total of 50 million tons by the year 2050; in this regard, 10 percent will be from LH_2, 17 percent e-methanol, and 73 percent through e-ammonia by using fuel cells and internal combustion engine (ICE).

The MDO burns more fossil fuel, which means emitting more GHG as opposed to H_2-based energy. However, when using an internal combustion engine for both H_2 and MDO, nitrogen oxide (NOx) emission is higher (Xing *et al.*, 2021). The utilization of internal combustion engines gives rise to fatal emissions such as nitrogen oxide (NOx), carbon dioxide (CO_2), methane (CH_4), black carbon (Zhang *et al.*, 2019), sulfur oxide (SOx), and carbon monoxide (CO). IMO (2023) states that limited GHG emissions are included in the MEPC 80, namely, CH_4, CO_2 and NOx. Even though other emissions exist and should be included in reducing GHG emissions, there are other priorities besides these. An example is implementing alternative green fuels such as H_2 using energy conversion technologies such as fuel cells. Valente *et al.* (2017) allude that alternative fuels are best suited for transitioning to a clean energy source. The volumetric and gravimetric energy density components of MDO and H_2 (liquid and compressed) (see Figure 1). The above parameters are crucial to the technology's economic costs and environmental performance. Fuel cells are of paramount importance in the efficient conversion of energy and in the reduction of emitting GHGs; therefore, using such technology to store GH_2 will help reduce global temperature and decrease global warming as part of the shipping decarbonization pathway.

The maritime industry is exploring alternative fuels and technology advancement, which is crucial in accommodating the maritime decarbonization pathway. Decarbonizing the shipping sector is essential in fulfilling the Paris Agreement (UNFCCC, 2015). Technology also plays a vital role in reducing GHG emissions; however, technological advancement requires thorough research, particularly on the alternative fuel (GH_2) and technology (fuel cells) inputs and outputs of product life span. In this regard, the development of GH_2 through the various production methods needs to be studied, namely through wind power. Even though there has been an increase in literature on the LCA of H_2 systems (Dicer, 2012; Lee *et al.,* 2022), more literature needs to be explored on the usage of H_2 fuel, storage, and technology, especially in the maritime industry and on different vessels. The LCA process proposed by the IMO (MEPC 80, 2023) focuses on the tank-to-wake and well-to-tank. These two system boundaries outline from input (H_2 production by wind power) to output (H_2 fuel usage by vessel). The adoption of LCA methodology by the maritime industry is to promote the reduction of GHG emissions, assist in reaching net zero carbon emission by using green fuel in doing so, assist in mitigating the emissions of GHGs of no less than 70% by 2040 as opposed to 2008 emissions (IMO, 2023).

Even though the maritime sectors proposed implementing LCA methodology to mitigate GHG emissions, costs are considered hindering as green fuel is a reasonably new avenue to branch into as an industry. There is a rising need to assess the economic feasibility of the product's life for future investment and adoption of alternative fuel prices or costs for market share purposes.

Hence, the importance of LCCA for both investment and operation costs. According to Dicer (2012), hydrogen annual production of 40 Mt market share was estimated at \$50 billion in 2011. However, at that time, it was not utilized for fuel but rather for chemical substances and in oil refineries. Furthermore, GH_2 is estimated at \$1.40kg by 2035 (Liu *et al*., 2023).

Hydrogen, mainly GH_2, is considered cost-intensive compared to fossil fuel-based alternatives. However, more initiatives and GH_2 production sites are being developed to reduce costs for global GH_2 production (IEA, 2023). IRENA (2023) states that by 2023, GH_2 can be cost-competitive with other alternative fuels. Numerous countries in the Global South are venturing into producing GH_2 cheaply to attract investors (India, Mexico, Brazil, and Morocco) (Green Hydrogen Initiative, 2023).

Problem Statement

The world is shifting towards a sustainable and net-zero energy source. This has led to increased exploration of H_2 as an alternative fuel for maritime transportation. As international regulatory bodies, including IMO, drive for greener shipping alternatives. To be precise, GH_2 through the production of renewable energy sources (wind power) has presented an avenue of plummeting greenhouse gas emissions and dependency on conventional fossil fuels. The need for an integrated approach that combines the LCA and LCCA for GH_2 poses a challenge for industry stakeholders in providing informed decisions.

Significance

The global warming event is of utmost importance thus far. Research has proved that shipping highly depends on fossil fuels (Valente *et al*., 2020). The high dependence on fossil fuels leads to increased emissions of greenhouse gases, making it the primary source of global warming on Earth. Oliver (2021), cited in Guven and Kayalica (2023), states that the shipping industry is among the top 7 emitters when arranged according to nations. Therefore, transitioning from conventional fossil fuels to low-emission fuels for maritime transport can reduce GHG emissions to zero. Accordingly, the research study uses the LCA (environmental) and LCCA (economy) to address the GHG emissions emitted by the maritime sector when utilizing fuels both conventional (MDO) and alternative fuels (GH_2). The emphasis will be on GH_2 fuels on a tanker carrier vessel with a two-stroke engine and compare with fuel cells. The vessel berths and bunkers in South Africa. This vessel was selected for the study to investigate LCA and LCCA potential using the GH_2 fuel option. This study can set a standard for a long-distance GH_2-powered seagoing ship to reduce emissions.

Aim and Objectives

Aim

The study explores the environmental impacts of the two different fuel types, mainly MDO and GH_2, using the LCA while investigating the economic feasibility performance involved in the fuel using the LCCA.

Objectives

I. To compare the life cycle and LCCAs of MDO and GH_2 fuel.
  - This will be achieved by analyzing both fuels' environmental impacts and economic feasibility, demonstrating the potential of implementing GH_2-fueled vessels.

II. To examine the combustion of both SOFC and internal combustion engines with both fuel types.
  - This exploration will consider the efficiency, emissions, and material used in internal combustion engines and SOFCs.

III. To verify the LCA methodology proposed by the International Maritime Organization compared to the IPCC.
  - The research will investigate the solid differences and provide subsequent recommendations.

IV. To quantify the potential GH_2 produced through offshore wind in a Saldanha Bay Port and the revenue generation.

Research Questions

To achieve the objectives mentioned above, the research will attempt to answer the following questions:

1. What are the environmental impacts of using H_2 as a maritime fuel, and how is it economically feasible compared to MDO?
2. How does the efficiency of SOFCs compare with internal combustion engines, considering the material used for each product?
3. Which LCA is more effective or practical between the IPCC-independent ISO14040 standard and the IMO lifecycle assessment approach?
4. How much GH_2 can OSW produce in a South African Port?
5. How much wind can the South African Port generate to produce hydrogen, and what are the financial implications?

Framework of the Study

The subsequent chapters of the research study are introduced in summary using a logical order as follows:

Chapter One: Introduction: Provide the content of the thesis, a summarized version of the entire dissertation with inclusion of background study, aim and objectives, methodology, and limitations.

Chapter Two: Literature review provided a systematic review of the literature published on the topics covered in the study to guide the background knowledge in a conceptual framework to understand the development of GH_2 fuel as an alternative fuel.

Chapter Three: Methodology, intended to provide, explain, and present the research methodology on which data collection method was utilized to complete the research study. Provide a case study and H_2 and LCCA techniques.

Chapter Four: Data Analysis This chapter presents the data findings of the research study and is thoroughly analyzed based on the results.

Chapter Five, Discussion of the results presented in the previous chapter.

Chapter Six, Recommendation and Conclusion, provides recommendations based on the study's investigation, deliberation, and conclusion on the study findings.

Conclusion

The chapter has highlighted that greenhouse gas emission is a global crisis, and the maritime sector is doing something about it, hence the decarbonization pathways of exploring alternative fuels and other propulsion technologies to mitigate the emissions. The introduction of alternative fuels, such as GH_2, is one of the critical steps in implementing the strategy. This can be achieved by in-depth knowledge of the life span of GH_2 from production to end-of-life, in this case, the usage stage.

Chapter 2: Literature Review

Introduction

The chapter aims to discuss the existing literature review on GH_2 as an alternative fuel by exploring the LCA of GH_2 for environmental performance. Furthermore, it explores the life costs assessment for economically evaluating the GH_2 on the vessel's lifespan.

International Maritime Organization vs IPCC

Maritime transportation has been the core of global trade. Over the years, the shipping industry has been trying to develop strategies to reduce GHG emissions to meet its 2050 goal of reducing 50% of CO_2 emissions. These strategies are targeted at the reduction of carbon intensity of seagoing ships. Over the years, the industry has been highly dependent on heavy fuel oil due to its abundance, infrastructure development, and low costs. However, due to its high pollutants of minerals such as heavy metals containing nickel, vanadium, and sulfur.

The maritime industries have, however, improved from the high dependence on heavy fuel oil as it has been associated with studies that indicate its environmental and human health risks about pollutants such as Nitrogen Oxide (NOx), Sulfur Oxide (SOx), and, Particular Matter (PM), and recently Black Carbon (0.65 x Particular matter) in the Arctic (Zhang *et al.*, 2019). Therefore, over the years, the International Maritime Regulator Body (IMO) has developed strict regulations to limit the presence of NOx and SOx on vessels. This is part of the end goal of reducing GHG emissions by 2050. In doing so, the stakeholders, such as the shipowner, have implemented modifications to operations and equipment to control air pollution onboard, such as the technology of catalytic reduction, SOx scrubbers, and alternative fuels.

The sector has come up with decarbonization pathways in ways to reduce GHG emissions by the maritime industry. As part of the GHG strategies, the IMO has included alternative fuels (methanol, ammonia, biofuels, H_2, LNG, and LPG (Shi *et al.*, 2023) as one of the essential methods in reducing carbon emissions. This is after the studies have proved that operations or combustion is one of the highest contributors to GHG emissions. Introducing strict standards has increased the deployment of alternative fuel as a pathway to decarbonize the sector. In addition, propulsion and power systems, voyage optimization, hull design, speed reduction, and market-based measures are part of the decarbonization pathway for international maritime.

Trivya *et al.* (2020) assessed that the technical actions undermine the reduction of GHG. Therefore, a holistic approach to reducing GHG emissions should include the overall system from feedstock to fuel consumption. This was considered a crucial option in quantifying the overall environmental consequences and advantages of applying alternative fuels in industry. Daioglou *et al.* (2020) touch on biofuel benefits; the author elaborates on ensuring that this fuel in LCA includes deforestation and land use changes. The recent IMO regulation on GHG emissions focuses on CH_4, $CO_{2,}$ and N_2O and excludes the rest, including black carbon; the regulatory body is still using AR6, which still has N_2O at 265, whereas the IPCC has published AR6 whereby N_2O is 273. Additionally, the IMO includes GWP100 and excludes the 20 to achieve the targeted goal of reducing GHG emissions in the shipping sector, which also provides energy conversion technology to accommodate net zero fuels such as H_2.

Energy Sources: Hydrogen

The high dependence on fossil fuels has been the main consequence of environmental issues concerning climate change. Therefore, it has motivated researchers to explore alternative fuels to mitigate greenhouse gas emissions. Even though other alternative fuels such as liquified natural gas (Bicer & Dincer, 2017; Awoyomi *et al.*, 2019), methanol (Bicer and Dincer (2017), ammonia (Perčić *et al.*, 2020), dimethyl ether (Schühle *et al.*, 2023; Park *et al.*, 2020; Perčić *et al.*, 2020) are being explored as well, to assist in reducing GHG emissions. The production of green molecules through renewable energy is essential to combat the dependence on fossil fuels (oil and gas), especially in the maritime transport space.

The maritime transport industry is estimated at 80-90% of global trade fuelled by oil and gas (UNCTAD, 2022; IRENA, 2022). H_2 as a fuel can assist in combating the dependency on fossil and drastically reduce emissions. Even though GH_2 is produced explicitly through renewable energy, other H_2 fuels are produced differently, for example, grey, blue, brown, yellow, and pink (Ajanovic *et al.*, 2022).

Adopting alternative fuels such as hydrogen introduces multiple impacts due to storage volume and energy density parameters. These factors affect maritime turnover time and cargo capacity, affecting bunkering and the vessel's endurance range. A volumetric energy density exceeding 1 indicates lower storage requirements per volume. Figure 1 illustrates that MDO requires less storage than hydrogen (LH2 and CH2), which have higher storage volumes than MDO. Similarly, a relative gravimetric energy density greater than 1 implies that hydrogen is lighter than MDO, which has a value of 1 or less. Consequently, hydrogen demands more storage space than MDO but offers greater efficiency. In this scenario, more storage and reduced refuelling frequency are necessary, potentially impeding maritime operations. As Brynolf et al. (2014) and Mohd Noor et al. (2018) discussed, the economic challenges of light fuels that require extensive storage have business implications for shipowners.

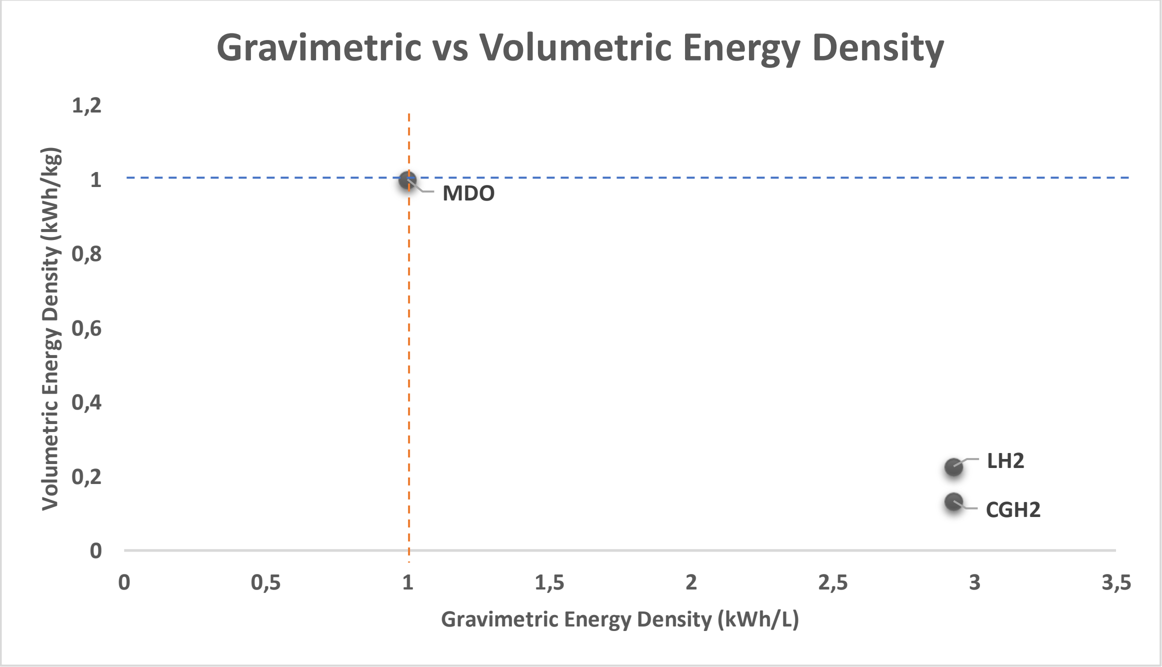

Figure 1 The gravimetric and volumetric energy density of marine diesel oil, liquid, and compressed hydrogen. Adopted from Wang et al. (2019)

Green Hydrogen Production

Hydrogen production over the years has evolved, offering diverse methods to produce H_2. In doing so, this has created an integration for future energy systems by reducing the dependence on fossil fuel-based energy to a more sustainable and cleaner energy source such as renewable energy. GH_2 is produced through water electrolysis, water splitting (photocatalytic and thermochemical), and water thermolysis, an element that produces electricity through GH_2 and hydro generation (Wang *et al.*, 2019). Ondrey (2020) and Ondrey (2020) stated that in 2025, a GH_2 plant that will be one of the largest in the world is planned to be built. The author states it will operate at a capacity of 650 tons of H_2 per day and will be produced through electrolysis and 4GW from wind, storage, and solar. According to (Atilhan *et al.*, 2021), GH_2 costs exist when using any renewable energy source. Even though that is the case, wind production is slightly best for environmental impacts. In particular, offshore wind turbine farms are more efficient, reduce GHG emissions, and are more environmentally acceptable if marine spatial planning is conducted thoroughly (Spijkerboer *et al.*, 2020).

Renewable energy sources produce GH_2 by using electricity through a process called electrolysis (water). This H_2 can be produced through wind, solar, biomass, nuclear, or hydropower (Li, 2017; Chou *et al.*, 2021). GH_2 is commonly known as being produced through solar and wind energy (EIA, 2023). GH_2 is considered more sustainable than others; other scholars in research define it as renewable, clean, and or low-carbon H_2. However, other scholars, such as Dawood *et al.* (2020), criticize the terms mentioned above, calling it universal; the authors further introduced a model (H_2 cleanness index model). The demand for clean H_2 energy is 0.1% in the shipping and heavy industries (IEA, 2023). This indicates the slow transition to clean energy as part of Net-Zero emissions by 2050.

The acceleration of implementation from policymakers is crucial for fast-track implementation. Even though some European countries have started implementing measures to decarbonize the maritime industry, the first H_2-fuelled ferry is in Norway (IEA, 2023). Literature states that it is debatable whether society can adapt to an H_2 economy (Loisel *et al.*, 2015; Lund *et al.*, 2015). This is after introducing an H_2-based energy storage system that has been viewed as less costly and still accommodates more extensive storage (Dawood *et al.*, 2020). Cetinkaya *et al.* (2021) conducted an LCA on the approach to H_2 production, which looked into five different methods to produce H_2 through the thermochemical cycle: water electrolysis (water energy-based and solar), natural reforming, and coal gasification.

Wind Energy Source

Wind energy is generated using wind power for electricity by using wind turbines for energy extraction. Wind energy rotates the wind turbine by converting kinetic to mechanical energy, which is further converted to electrical energy. From the wind source of energy, alternating current (electricity energy) is extracted; therefore, both the alternating current and direct current converter are used to pump electrical power (direct current) to the electrolyzer to produce H_2 (Wang *et al.*, 2019; Pereira & Coelho, 2013). In categorizing wind turbines, there are two classifications: on and offshore wind turbines based on geographic location and form of installation (Enevoldsen *et al.*, 2021).

Offshore wind turbines are installed on open water, offshore with abundant wind resources. The cost of electricity from wind power compared to 2021 for onshore wind decreased by 2%, whereas for offshore, it increased by 2% (IRENA, 2022a). The offshore site has visual (Gkeka-Serpetsidaki *et al.*, 2022; Maslov *et al.*, 2017) and acoustic impacts (Marmo *et al.*, 2013; Mooney *et al.*, 2020); vessel traffic (Yu *et al.*, 2020). In Atlantic Canada, a 3.2-million-euro offshore wind energy project was approved for installing wind turbines and the capability in glacial seabed (Collins, 2021). Nevertheless, offshore wind turbines are considered to have abundant resources and are affordable; however, the maintenance and operations tend to be expensive due to site accessibility, cabling, and performance of turbines. Concerning cabling, the maintenance is influenced by weather conditions.

Figure 2 below illustrates the extraction of electrical energy from wind, converted from alternating to direct current and used as an electrolyzer to split water into H_2 and oxygen. According to Oruc and Dincer (2021), water breaking using the Cu-Cl cycle is an advantage for renewable energy. However, the electrolyzer can also use wind-based electricity for H_2 production and can be utilized in mobile (vessels, vehicles) or immobile fuel cells to generate electricity (Pereira & Coelho, 2013). The H_2 energy can also be stored for days without wind or a low wind speed interval. Therefore, it illustrates that wind energy technology is sustainable, clean, and efficient for H_2 production.

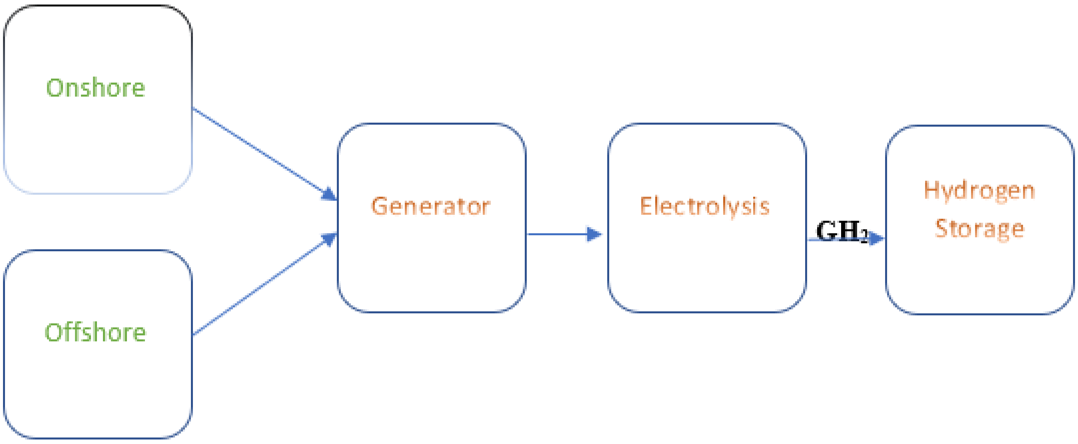

Figure 2 Wind-Based Hydrogen Production Process

Electrolysis

Electrolysis and electricity grid combined create a cross-function of a system generating H_2 and an electricity grid that balances the device as it works during stages of additional grid electricity (Scamman & Newborough, 2016; Götz *et al.*, 2016). When dealing with electrolysis while managing a quick start-up and switching off with extreme resistance concerning power fluctuation to limit losses. Three electrolyzers, SOE, PEM, and AFC, already exist, which shows that the potential of transitioning to H_2 for environmental purposes to produce GH_2, transport, and store it is close to near and possible.

Hydrogen Storage

The hydrogen fuel cells can be utilized in vessels, vehicles, and residences. Furthermore, it can be used for combustion for thermal energy production to heat water and to keep warm. Therefore, using an H_2 system can decrease global temperature and reduce GHG emissions while reducing the grid load using fuel cells. The transportation sector for boats (Torvanger, 2021; Wang *et al.*, 2022; Perčić *et al.*, 2022; Guven & Kayalica, 2023), vehicles (Bicer & Khalid, 2020) and aviation (Bicer & Dincer, 2017) is slowing transitions or looking into transition to better and clean fuel for the environment. There are two classifications of H_2 storage, namely, physical and material-based technology. Otherwise, material and solid storage include absorption methods, which entail chemical and physical sorption.

Hydrogen Supply, Transportation, and Infrastructure:

Hydrogen production, when used in fuel cells or combustion, emits fewer GHGs than conventional fuels, making it pivotal for decarbonizing the maritime sector. Thus far, applying GH_2 in the marine industry demands specific considerations. While conventional fuel infrastructure has long been in place, suitable infrastructure for GH_2 bunkering and storage at ports must be established, given the need for large-scale storage due to H2's lower energy density than MDO (Sundén, 2019). However, this transition may be influenced by regulatory requirements for renewable energy sources. Port designs may need adjustments to accommodate alternative fuels, incurring potential costs, and the choice between liquid or compressed storage methods remains under scrutiny. Distribution of H_2 can occur through tank transport, loading, and supply to vessels for export or onboard use.

Hydrogen Costs

The global costs of H_2 are highly influenced by the production and compression system and the energy utilized for production levels. For instance, the H_2 price in Europe is less when transported as ammonia to the continent than when transported as a liquid. This is because the amount of energy still needs to be used to convert ammonia to LH_2. Therefore, costs are less when sold as ammonia than liquid H_2. The form of production can also influence prices, be it SMR, coal gasification, or RE. IRENA (2022) predicts that shortly (2040-2050), GH_2 costs will decrease due to accessibility and cost reduction of electrolyzers and low electricity prices.

Hydrogen Regulations

The safety considerations associated with the use and transportation of liquefied hydrogen aboard ships are also outlined in IMO (2016). Furthermore, this source references regulations and guidelines provided by ship classification societies, which outline the necessary classification requirements for fuel cell system, focusing on safety, fire protection, management, regulations, and monitoring (DNV, 2018; Indian Register of Shipping, 2021). A well-defined legal framework is necessary for classification societies to conduct assessments of marine vessels at all stages of their development, construction, and installation (American Bureau of Shipping, 2020). Any remaining undefined legal aspects and potential ambiguities are identified and addressed through a risk assessment (Haugom *et al.*, 2018; Aarskog *et al.*, 2020). The author also explored other standards that have been either applied or developed to meet the requirements of global systems and discusses their potential impact on the use of hydrogen in marine applications (Technical Committee: ISO/TC 107, 220)

Furthermore, it emphasizes the importance of safety and regulatory compliance when dealing with hydrogen on ships. It highlights the role of ship classification societies in establishing and enforcing classification requirements related to fuel cell systems. However, it raises concerns about the lack of a clear legal framework, which necessitates comprehensive assessments of marine vessels at various stages of their development. Therefore, it highlights the significance of risk assessment in identifying undefined legal aspects and addressing potential ambiguities. This approach is crucial in ensuring safety and compliance without a well-established legal framework.

Additionally, the mention of standards developed for global systems that may impact hydrogen use in marine applications emphasizes the need to adapt and extend existing standards to accommodate the unique challenges of using hydrogen as a maritime fuel. This highlights the complexities and considerations that come into play when integrating innovative technologies in the maritime industry.

Hydrogen Challenges and Opportunities

The sudden interest in GH_2 is increasing as industries become aware of the environmental impacts of conventional fuels, hence the transition to renewable energy sources. Green hydrogen costs, infrastructure, bunkering, storage, technology development transportation, and commercial variability are currently challenging. GH_2 is cost-intensive compared to natural gas. Even though it's still a new concept in the maritime industry, investments in GH_2 are considered risky; however, this does not prevent stakeholders such as shipowners and the fuel industry from diversifying their portfolio on alternative fuels such as GH_2. Electricity produced by renewable energy is much cheaper than natural gas (Ishaq *et al.*, 2022). H_2 production costs in developing nations are or will be slightly more affordable, which means that exploitation can occur for H_2 production in developing countries. Therefore, it opens room for financial and technological obstacles, as the electrolysis process is costly due to high electricity demand (Terlouw *et al.*, 2022). The costs of renewable H_2 have critical financial consequences. The cost implications are roughly related to the minimum implementation of renewable H_2, but this energy source yields reasonable environmental costs as opposed to the others (Baykara, 2018).

Fuel Cells

Table 1: Fuel Cell Specifications. Adopted from: Sundén (2019)

Fuel Cell Type	**Electrolyte**	**Efficiency (%)**	**Temp °C**	**Reaction**	
				Anode	**Cathode**
Proton Exchange Membrane Fuel Cell (PEMFC)	Nafion, Platinum	40 - 50	30 - 100	$H_2 \rightarrow 2H^+ + 2e^-$	$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Alkaline Fuel Cell (AFC)	Nickel Tetrafluoroethylene	50 - 60	50 - 200	$H_2 + 2(OH)^- \rightarrow 2H_2O + 2e^-$	$\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$
Molten Carbonate Fuel Cell (MCFC)	Molten Carbonate	60	~ 650	$H_2 + CO_3^{-2} \rightarrow H_2O + CO_2 + 2e^-$ $CO + CO_3^{-2} \rightarrow 2CO_2 + 2e^-$	$\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_3^{-2}$
Solid Oxide Fuel Cell (SOFC)	Yttria Stabilized Zirconia (YSZ)	45 - 65	500 - 1000	$H^2 + O^{-2} \rightarrow H_2O + 2e^-$ $CO + O^{-2} \rightarrow CO_2 + 2e^-$ $CH_4 + 4O^{-2} \rightarrow 2H_2O + CO_2 + 8e^-$	$\frac{1}{2} O_2 + 2e^- \rightarrow O^{-2}$

The H_2 fuel cell system can be used in residential areas, large, heavy industries, and transportation. In the residential and for propulsion, the fuel cells that will be more suitable are PEMFC, AFC, and SOFC (Fernández-Ríos *et al.*, 2022). Furthermore, the response of fuel cells includes cathode and anode. Whereby fuel moves through bipolar electrode power (anode) into the fuel cell as the cathode experiences oxygen flow (Ajanovic *et al.,* 2022). Table 1 above provides the characteristics of varying fuel cells. From the list above of fuel cells, the crucial one is for the transportation industry (maritime). For example, MF Hydra is a ferry fuelled by liquid H_2 from Norway (Laasma *et al.*, 2022). This vessel indicates the recent development of alternative fuels used in the maritime sector. It also shows that the maritime industry is indeed investing and implementing the transition to a carbon-neutral or even carbon-free industry. Therefore, GH_2 in the marine sector and transportation is paramount. This can contribute to reducing GHG emissions, carbon credit, and environmental issues; this can help transition from traditional energy sources to renewable energy sources such as solar, hydropower, nuclear, and wind.

The advantages of these fuel cells are, firstly, highly reliable energy conversion technology with a maximum efficiency of 65% (Sundén, 2019; Williams, 2018); secondly, they accommodate at any temperature depending on the type of fuel cell suitable for the task. Additionally, these materials still require mass production if the transition to alternative fuel is fast-tracked by the IMO and IPCC. SOFC has high-quality waste heat recovery (30-40%) on board with minimal pollution and acid rain, especially with H_2 fuel, even though there are high CO_2 emissions during the construction phase of the SOFC, see Table 2 below: as it outlines the environmental impacts of SOFC energy-based system value chain using ReCiPe 2016.

Table 2 Environmental Impacts of SOFC. Adopted from Mehmeti et al. (2018)

Environmental Impact	**SOFC [25 kW]**
Global Warming Potential (kgCO2eq)	0.523
Stratospheric Ozone Depletion	0.142
Particular Matter Formation	83.3
Photochemical Oxidant Formation	516
Terrestrial Acidification Potential	330
Freshwater Eutrophication Potential	12.1
Mineral Resource Scarcity	0.83
Fossil Resources Scarcity	0.184
Water Consumption Potential	101
Cumulative Exergy Extraction	8.509

Fuel cells are considered one of the promising conversion technologies and are also considered to have reduced GHG emissions as opposed to other power generation technologies. According to Damo *et al.* (2019), the SOFC presiding environmental impacts the reduction of carbon dioxide, air pollution, NOx, PM, SOx, CO, and organic compounds. The emissions of SOFC are primarily influenced by fuel type and power production. For instance, wind-based H_2 for water electrolysis has lower environmental impacts than conventional fuel and other alternative fuels such as LNG, ammonia, and methanol (Bicer & Khalid, 2020). However, due to the costs of GH_2, this can be a challenge in transitioning to renewable-based energy sources such as GH_2 at a fast pace.

Internal Combustion Engine

The global temperature rise of 1.5°C is due to GHG emissions, and mitigating that from the maritime industry must be through fuel type and internal combustion engines. Over the years, the internal combustion powered by H_2 has improved from SI engines (Spark Ignition Engines). Thus far, improvements have been made to the power density of H2-fueled engines. H_2 ICE, over the years, has developed from liquid to direct injection. Direct injection is one of the best-selected advancements concerning the H_2 ICE development in preventing preignition by increasing volumetric efficiency.

Application of LCA

Society is shifting towards more environmentally friendly products and services as they become more ecologically aware. Industries are being regulated (IPCC) to move towards sustainable products, hence the introduction of LCA. The ISO 14040 and 14044 standard series define LCA as a method utilized to assess and analyze a product's whole life cycle, which consists of the raw materials accumulation, production, consumption, and disposal (Vellini *et al.*, 2017).

The application of LCA can be extended to various industries, such as energy generation (Prasad *et al.*, 2020; Vellini *et al.*, 2017), transportation (Fries & Hellweg, 2014; Liu *et al.*, 2023; Wang *et al.*, 2022; Huang *et al.*, 2022; Chen & Lam, 2022; Bicer & Dincer, 2017), and recently on shipping (IMO, 2023; Yin *et al.*, 2021). Identifying the environmental impacts of a product is crucial in identifying opportunities to improve the product, hence the importance of employing LCA. In the maritime context, LCA is explored to compare alternative fuels' environmental impacts (Zhu *et al.*, 2018; Chen & Lam, 2022; Gilbert *et al.*, 2018; Bicer & Khalid, 2020; Lee *et al.*, 2022; Bicer & Dincer, 2018) as a solution to assist in reducing greenhouse gas emissions in the sector while enhancing the products environmental profile. The LCA tool has four initial steps: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. These phases are interconnected; therefore, the connection determines how the other steps are concluded. Consequently, a stage can only be considered final if the entire LCA study is completed.

Goal and Scope

The goal and scope define the study's aim and objectives of what the study is trying to achieve. This is implemented through examining the product, systems, or services. The focus is mainly on the inputs, such as raw materials from natural resources, and the output of the emission, ideally related to nature (Chen *et al.*, 2020; Jeong *et al.*, 2018; Li *et al.*, 2014). In the goal and scope stage, the LCA needs to be well-defined. In the case of the goal, it must be explicit regarding the application, the rationale, the audience, and whether the study results are comparative.

The quantity of the product is essential for the inputs and outputs. For instance, shipping sector and maritime academic researchers have utilized 1 kWh FU (Rillo *et al.*, 2017) and MJ/kg (Haung *et al.*, 2022). The study by Rillo *et al.* (2017) states that the FU is 1 kWh for the electricity produced by SOFC systems (SOFCs) compared with ICE using sewage biogas.

The system boundary is set on a repetitive process wherein a fundamental system boundary is selected and clarified by including additional unit processes proven significant through a sensitive analysis. This can be perceived as one of the challenges associated with system boundary criteria as it can be subjective (Li *et al.*, 2014).

Life Cycle Inventory Analysis

The LCA includes a quantification process whereby the extraction of raw materials, emissions, and energy are included in the life cycle of the service, product, or service. In this case, greenhouse emissions from land, resource use, atmospheric and water emissions are included. Limitations may vary, hence the additional emissions within an LCA inventory analysis of each project or study. For instance, a flow model is required to develop the LCA inventory to illustrate the activities in the LCA's system boundary.

The inventory requires arranging data collection per the study goal and scope. Preliminary data are original data from the first hand, and secondary data are retrieved from an LCA database or software (GaBi, GREET, SimaPro, Ecoinvent, and ReCiPe) and literature. The data collected also requires evaluation, therefore utilizing a pedigree matrix for having quality LCI data.

Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) is the next phase after LCI. It focuses on the potential impacts of the product lifecycle. In achieving these potential environmental impacts of a product or a study, selection, classification, and characteristics steps are essential to consider. For instance, GWP100 is expressed using carbon dioxide emissions equivalents (CO_2-Eq) (IPCC). The impacts of LCA are required on all the phases of the product lifecycle, from raw material to disposal.

Interpretation

This phase of the LCA is crucial in quantifying, evaluating, and identifying results collected from LCI and LCIA. The interpretation phase can be viewed as a study recommendation or conclusive stage of LCA. It is crucial to identify essential issues, evaluate the sensitivity, and conclude by considering the study's limitations and providing recommendations. Michalski and Krueger (2015) state that interpretation must add to the body of knowledge for future areas to investigate and identify.

Life Cycle Cost Assessment

LCCA, supported by the IMO for the 2050 decarbonization pathway in shipping, has gained international shipping research popularity. It assesses a product's total costs throughout its lifespan, considering discounted rates and capital costs (Dinu & Ilie, 2015; Ren *et al.*, 2020; Perčić *et al.*, 2022; Ayodele, 2019). These costs encompass investments, raw materials, production, operational and maintenance expenses, disposal, and other associated costs. LCCA's stages reflect those of LCA, with Net Present Value (NPV) as a common calculation method. This approach, increasingly embraced in the maritime sector, combines environmental impact and economic evaluation for alternative fuels and technologies in research and policymaking.

Conclusion

The chapter discussed the literature IMO and IPCC pathway to decarbonization from alternative fuels (hydrogen). They reviewed existing literature on hydrogen and the energy sources (wind) to produce hydrogen. The chapter employed a conceptual framework for LCA and the LCCA. Furthermore, it explored the energy conversion technology of SOFC and hydrogen on ICE and the economic and environmental implications and challenges associated with green hydrogen as a fuel.

Chapter 3: Methodology

Introduction

This chapter aims to stipulate the methodology explored in the study as it covers the systematic review of LCA and LCCA methodology, including the case study of the wind production description and the economic evaluation of wind production to accommodate the vessel. The wind data is collected for two years. Furthermore, it presents the equations of the output and provides vessel description. This section outlined a summarized literature review in a tabulated format to better understand what other authors had covered.

Systemic Review

The research study employed a system review to achieve the study's objectives; a gradual analysis of LCA and LCCA for GH_2 and MDO is required.

A systemic review was employed to gather all the required data on the literature that has been peer-reviewed on the LCA and LCCA methods. According to (Zumsteg *et al*., 2021), the LCA is an international standardized technique used to evaluate and report studies on LCA. This chapter will further discuss the two methodologies employed in this study.

Limitations/ Delimitations for the selection of articles utilized in this study:

1. The study included all peer-reviewed articles published in reputable journals.
2. Publication year is restricted to 10 years (2013 – 2023) were considered. Even though the first set of ISO14000 - 14040 (LCA) was completed in 2000, the study remains to use recent literature that defined LCA.
3. All articles were published in English.

Table 3 below illustrates the literature related to the study.

Procedure

1. The search was on Scopus, Research Gate, and Google Scholar databases, utilizing Boolean and keywords to gain access to the articles. Using keywords
    - "LCA of GH_2," 'Maritime GH_2," "LCA of H_2 Fuel," "LCA of H_2 Fuel," LCA of Alternative Fuels for Maritime"

    - "LCA of Fuel Cells," "LCA of Internal Combustion Engine and H_2," "GH_2 in South Africa", ".
    - "LCCA for H_2 Fuel," "Life Cycle Cost of H_2," "LCCA for Maritime H_2 Production," "Wind-based production of hydrogen," "Alternative fuels for Shipping Sector"
2. Books (H_2 Economy, H_2, Batteries and Fuel Cells"
3. Website "GH_2 in South Africa," IMO Publications
4. A total of *n*= 125 articles were downloaded from Scopus, Research Gate, and Google Scholar.
5. Articles downloaded were filtered, and a duplicate check was conducted using Microsoft Excel and manual review. *n*= 7 duplicates. They were then removed manually.

Screening

The screening criteria involved the inclusion and exclusion of articles. The articles that focused on the environmental impacts and economic evaluation of H_2 using the LCA and LCCA methodology were utilized in the systemic review of the study. The study criteria were limited to process-based LCA articles, as the process-based provided accurate and finalized analysis. This included a) technical properties (such as feedstock, primary energy source, H_2 production, H2 storage, and energy conversion technology) and b) LCA methodology (such as goal scope, FU, systems boundary, geographical scope, inventory, impact assessment, and interpretation).

As for the exclusion of the literature entailed:

i) LCA and LCA of H_2 before 2013,
ii) did not employ LCA. The number of articles that were excluded was *n=10.*

Structure

The structure of the methodology is as follows:

a. The offshore wind production
b. Life cycle assessment
c. Life cycle cost assessment
d. Systemic literature about LCA and hydrogen fuel

e. Vessel specification

Offshore Wind Production

The study focused on offshore wind-based hydrogen production for a chemical tanker. Wind production estimates were generated using Copernicus climate data and coded using Python IDLE Shell 3.11.5. The data was then exported to Microsoft Excel to create graphical representations (Figures 7 and 8).

Equations (1, 2, 3) used in the study facilitated the coding of wind data. The data collection took place in the vicinity of Saldanha Bay Port, a proposed site for green hydrogen production, situated at 33.00 Latitude and 17.56 Longitude. The code incorporated parameters from Copernicus and the turbine's diameter, including area, capacity, air density, energy, efficiency, wind speed, and wind power. Data collection occurred hourly over two years (2021-2022) and was managed for a single turbine, with specifications ranging from 0 to 4.5 MW.

Wind Speed

$$\sqrt{\left(\boldsymbol{U_i^2 + v_i^2}\right)}$$

Equation 1

Equation 1 above calculates the wind speed from different directions, with *U* being horizontal East and *V* being vertical North winds.

Wind Power

$$\left({}^{\mathbf{1}}\!/_{\mathbf{2}} \cdot \boldsymbol{A} \cdot \boldsymbol{C_p} \cdot \boldsymbol{\rho} \cdot \boldsymbol{V^3}\right)$$

Equation 2

Where:

A is area for the (m^3)

Cp co-efficiency or capacity factor of the turbine pitch angle of speed ratio over a period with a rated capacity of a similar period (time).

ρ the air density (kg/m^3)

Betz limit is *0.5* at its maximum value.

The wind speed variable can assist in calculating the *Cp* maximum by being able to adjust wind speed.

Energy

$$\frac{E_{(k-1)}+P_{w(k)}kWh}{1000}\ kwh$$

Equation 3

Where:

E represents energy, and *K* is the value that refers to different operations. *Pw* is for wind power divided by *1000* to convert to [*kWh*].

To achieve data on a turbine's energy generation for hydrogen production, a 120-diameter turbine was employed. This data aids in understanding the wind's production capacity and reliability for generating hydrogen to power a 7954-horsepower (5931 kWh) chemical tanker vessel. A life cycle assessment of wind energy via the turbine was conducted to obtain emissions data for the wind turbine.

Life Cycle Assessment

The LCA has four phases, which have been explained using literature in Chapter 2, namely: a) goal (objective) and scope (boundaries) definition; b) life cycle inventory analysis (LCI); c) Life cycle Impact Assessment (LCIA); and d) Interpretation. Figure 3 below represents the framework for LCA.

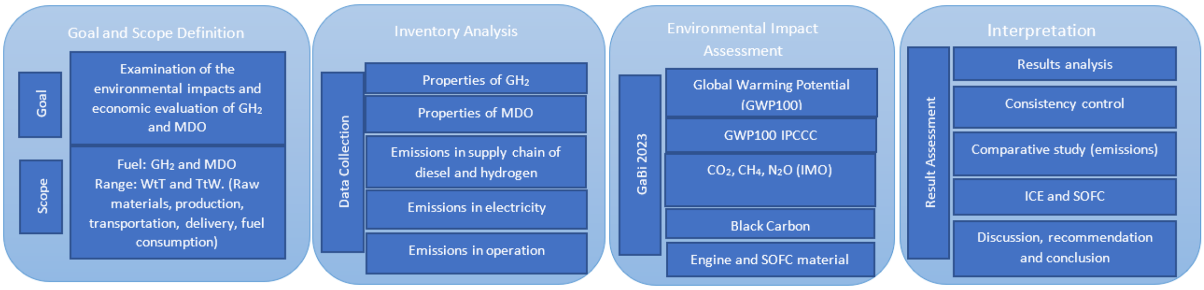

Figure 3 The LCA structure for GH_2 and MDO adopted from Guven and Kayalica (2023)

Phase 1: Goal and Scope Definition

This study aims to compare the environmental and economic aspects, including emissions, of two maritime fuels, GH_2 and MDO, over a 30-year lifespan of a two-stroke tanker. The assessment covers GH_2 and MDO fuels and analyzes materials, efficiency, and emissions related to GH_2 ICE, SOFC, and MDO.

To ensure objectivity, a Functional Unit (FU) of 1 kWh of energy generated at the propeller shaft is used for the study. The analysis includes two technologies: ICE compared with MDO and GH_2 and SOFC exclusively with GH_2. SOFC replacements occur every six years, and specific materials require periodic replacement.

The study relies on GaBi and Ecoinvent software for modeling emissions and energy flow, providing a robust database for comparative fuel emissions analysis. The system boundary encompasses Well-to-Tank (WTT) and Tank-to-Wake (TTW). WTT considers operations from raw material extraction to fuel consumption, while TTW focuses solely on emissions related to fuel consumption, excluding prior processes.

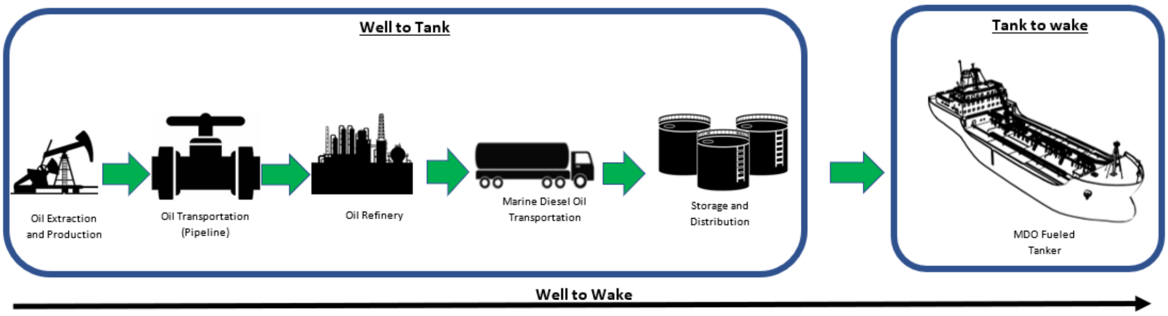

Figure 4 System boundary of Marine Diesel Oil

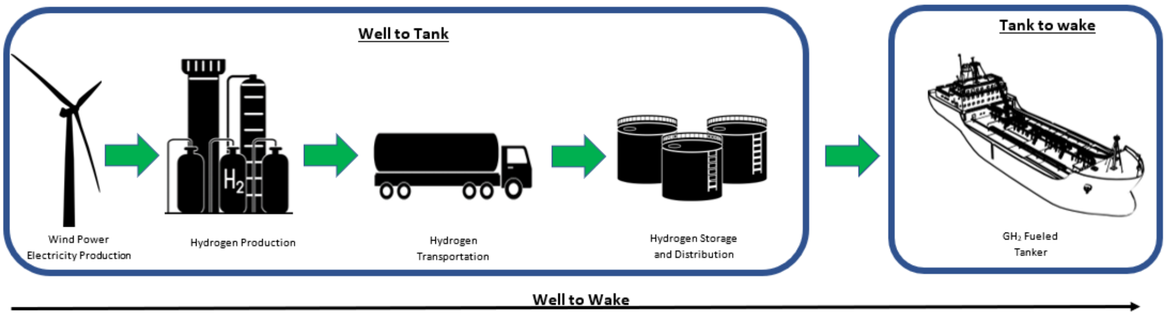

Figure 5 System boundary of Green Hydrogen

The feedstock utilized in this study is wind power generated by offshore wind turbines, which are used to produce GH_2. This hydrogen-based fuel powers a 2-stroke vessel that docks at the South African port of Saldanha Bay, where GH_2 is produced. The materials for the ICE and SOFC were adopted from Rillo *et al.* (2017) and subsequently modified to suit the dimensions and requirements of the vessel in question.

The study comprehensively considered the engine (1) and the fuel (2), encompassing their production and usage phases. It's important to note that the guidelines provided by the IMO exclusively address fuels, whereas this study offers a more holistic analysis, covering both the engine and fuel aspects.

Summarized scope:

- LCA of MDO and GH_2
- H_2 ICE and SOFC, and MDO ICE (materials, emissions, and energy efficiency)
- WTT (MDO and GH_2)
- TTW (GH_2 and MDO)
- Black Carbon

Inclusion and exclusion criteria:

- The study is focused exclusively on South Africa, with a specific focus on Saldanha Bay, as the site for GH_2 production.
- Operation costs related to fuel and lubrication oil have been excluded from the analysis due to insufficient available data.
- The end-of-life aspects of the study have been excluded due to a lack of comprehensive literature on the recycling of fuel cells.
- Water depletion considerations have been excluded from the study since available data indicates that South Africa is exploring the use of seawater for water electrolysis in GH_2 production, making water depletion calculations unnecessary

Phase 2: Life Cycle Inventory Analysis

The Life Cycle Inventory phase is where data collection, compilation, allocation, and calculation take place to assess the inputs and outputs of the system. Zhou & Pedersen (2018), data allocation can be categorized as generic or specific, depending on the study's requirements. In this research study, specific data collection (as depicted in Figure 3) above was chosen, extending to alternative fuels, such as GH_2 and MDO, using GaBi and Ecoinvent. This involved collecting primary and secondary data encompassing emissions, energy efficiency, materials, and Environmental Impact Assessment (LCIA).

The WTT stage included the production of fuel, encompassing processes such as transportation, bunkering, refinery, electrolysis, and fuel reforming, which were relevant to the study. MDO was considered as produced by well-known oil-producing countries. For GH_2, produced in South Africa using offshore wind turbines for electricity production, the WTT stage encompassed processes such as water splitting, electrolysis, and fuel delivery, categorized as WTT for each fuel type.

The TTW emissions considered in the analysis pertain to operations and air pollution, including GH_2 and MDO fuel consumption during operation.

Phase 3: Life Cycle Impact Assessment

The research study evaluated potential environmental impacts through LCI results. This phase encompassed a thorough examination of the environmental effects associated with the products in question, covering resource consumption and emissions across all stages of their lifecycles.

The analysis relied on software, specifically GaBi and Ecoinvent, to provide emission factors for GWP100, including 264 emissions. However, only specific emissions relevant to the study were utilized. At each stage, unique emissions were derived based on the processes and products involved. These stage-specific emissions were then aligned with GWP100 emissions, and the emissions corresponding to GWP100 were calculated and converted to a Functional Unit (FU) of 1 kWh. This approach was taken to ensure the study's accuracy and to avoid incorporating emissions unrelated to the product emissions and those associated with GWP100.

The system boundary includes both 'Well-to-Tank' (WTT) and 'Tank-to-Wake' (TTW) stages (as shown in Figures 4 and 5) above, emissions, and materials for both MDO and GH_2. Specific data on fuel consumption was obtained from the Battelle Memorial Institute (2016), and emissions produced at each stage within the system boundary were aligned with GWP100 impact categories for the production and use of MDO and GH_2. Notably, black carbon emissions were considered individually, with their inclusion in MDO but exclusion from GH_2. Other emissions were incorporated to create a comprehensive framework for the assessment.

Global Warming Potential

The life cycle inventory is performed on LCA as the third phase. Therefore, Global Warming Potential (GWP_{100}) is calculated as:

a. IPCC:

$$\boldsymbol{GWP_{100} = 1 \times CO_2 + 28 \times CH_4 + 273 \times N_2 0}$$

Equation 4

b. IMO:

$$\boldsymbol{GWP_{100} = 1 \times CO_2 + 28 \times CH_4 + 265 \times N_2 0}$$

Equation 5

Where:

GWP_{100} is Global Warming Potential

CO_2 is Carbon Dioxide

CH_4 is Methane

$N_2 0$ is Nitrous Oxide

The calculation of GWP100 for electricity production through wind for green hydrogen production is an integral part of the analysis. To determine this, the study utilizes the GaBi and Ecoinvent software, which covers the entire life cycle of wind turbines, from production to end of life, and the electricity generated. The electricity production from wind for hydrogen production is assessed in conjunction with GWP100 emissions according to the AR6 methodology of N_2O, which has a GWP100 value of 273 (IPCC, 2023)

Phase 4: Interpretations

The final phase, where the collected data will be discussed to draw meaningful conclusions. The interpretation of results will focus on comparing the environmental impacts of GH_2 and MDO over the 30-year lifespan of a tanker vessel, considering the use of SOFC and ICE.

Life Cycle Cost Assessment

The economic aspects of GH_2 and MDO is performed through a LCCA. This evaluation primarily considers investment, operational, and maintenance costs associated with both fuels, as well as the financial benefits of the project or product. The LCCA is applied with a focus on the 'tank-to-wake' perspective.

To assess GH_2, the study employs metrics such as Net Present Value (NPV) eq. 7, Payback Period (PBP) eq. 8, Internal Rate of Return (IRR) eq. 9, and Carbon Credit and credit costs (eq. 11). Carbon Credits are calculated for every ton of MDO without a cap. Manufacturing and infrastructure costs are excluded. It's important to note that the study should also incorporate 'tank-to-wake' assessments to provide a comprehensive understanding of system costs.

The LCCA compares the economic evaluation of MDO and GH_2 on a tanker, considering the entire process from well to tank and tank to wake. The Functional Unit (FU) represents the quantified performance of 1 kWh. The LCCA is focused on hydrogen production from wind turbines, considering investment and operational costs, as well as the inflation rate of South Africa (7.19%), over a 30-year lifespan.

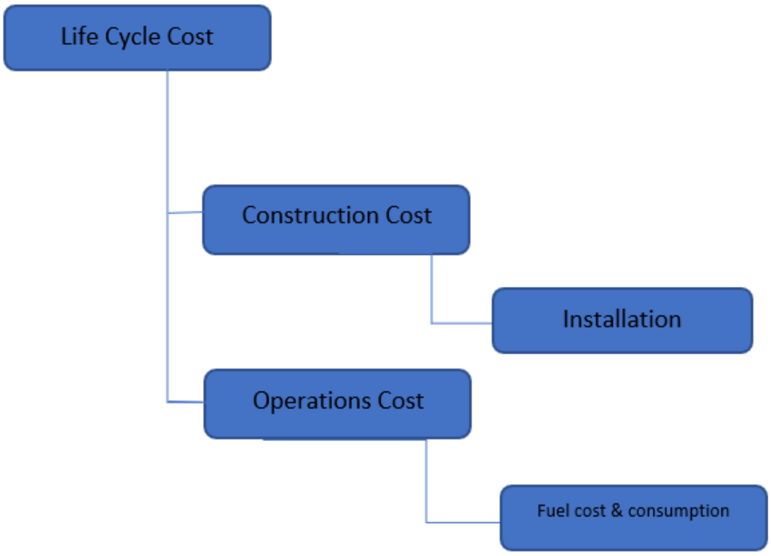

Figure 6 Life Cycle Costs Assessment Breakdown of ICE and Fuel Cells

Construction

The construction costs for both MDE and SOFC are estimated. These estimates encompass all the primary components required for construction. It's worth noting that this section requires further breakdown due to insufficient price information. Nevertheless, it's important to emphasize that all the estimation costs provided include expenses related to installation and construction.

Operations

The pivotal aspect of this phase involves assessing the fuel consumption of MDO and GH_2 when used with ICE and SOFC. The measurements are presented in terms of annual hours of operation and fuel consumption (FC) over a 30-year period, taking into account the possibility of fluctuating prices and fuel consumption rates over time. It is important to note that lubrication oil data was not included due to data limitations. Therefore, the equation used to calculate fuel consumption is as follows:

$$\boldsymbol{FC = \sum_{i=1}^{n} P_i \times SFOC_i \times hr_i}$$

Equation 6

Where:

FC is for annual fuel consumption (ton), then calculated to 30 years.

P is expressed in (kWh) of the engine power for operations.

SFOC in [g/kWh] of specific fuel consumption, and *hr* is for annual operating hours.

The study also incorporated the NPV equation 7 to find out the costs of the net present value of the generated energy.

$$\boldsymbol{NPV = C_I + \sum_{n=I}^{n} \frac{AC_n}{(1+r)^n}}$$

Equation 7

Where:

Net Present Value, is a financial metric that involves discounting cash flows from an investment to their current value using the capital cost. Calculating NPV is a method for assessing the balance between the benefits and costs of a project while considering the time value of money. In this context, NPV is computed over the 30-year lifespan of the vessel.

In the formula, C_1 represents the investment costs over the 30-year life span of the wind turbine, *AC* stands for the annual operational costs of the wind-based hydrogen project, *n* represents the year under consideration, and *r* represents the discount rate.

Payback Period

The payback period is the number of years/ months a project can pay back its primary investment costs.

$$\boldsymbol{PBP = \sum_{n=0}^{n} + \frac{AC_n}{(1+r)^n} = 0}$$

Equation 8

Where:

NPV is a Net Present Value

AC is the annual cost for the wind-based hydrogen project operation.

n is a year, and

r is the discounted price

Internal Rate of Return

The IRR measures the size of investment returns and capital costs equal to zero NPV.

$$\boldsymbol{IRR = \sum_{n=0}^{n} \frac{AC_n}{(1+r)^n} = 0}$$

Equation 9

Where:

NPV is a Net Present Value

AC is the annual cost for the wind-based hydrogen project operation.

n is a year, and

r is the discounted price

Levelized Cost of Hydrogen

The levelized costs of hydrogen (*LCoH*), as outlined by IRENA in 2021, served as the basis for determining the cost per kilogram of hydrogen and for calculating the initial project costs associated with using wind turbines to produce hydrogen for maritime transportation. In this analysis, both capital expenditure (*Capex*) and operational expenditure (*Opex*) were considered, considering South Africa's inflation rate of 7.19% (SARS, 2023). The estimated lifespan of the wind turbine was set at 30 years.

$$\boldsymbol{LC_0H = Capex + Opex + Tax}$$

Equation 10

Where:

LCoH is the levelized cost of Hydrogen.

Capex is the capital costs.

Opex the operation costs and

Credit (Tax) of South Africa

Externalities were excluded.

Carbon Credit

$$\boldsymbol{CCC = \sum_{n=1}^{30} TTW_{A,n} \times CP_n}$$

Equation 11

Where:

CCC is Carbon Credit Cost

30 is the vessel's life span.

$TTW_{A,n}$ is Tank to Wake of the annual emissions of fuel during operations

CP is carbon allowance.

n is year

Authors	**Size(s)**	**Fuel(s)**	**Application**	**Functional Unit**	**System Boundaries**	**GWP (100)**	**Acidification**	**Photochemical Ozone Creation Potential**	**CO_2, CH_4 & N_2O**	**Particular Matter**	**Energy resource demand (kWh)**	**Material resources demand**	**LCA Software**
Strazza *et al.*, (2015)	250 kWh	Natural Gas, biogas & power generation	Household	1 kWh	Fuel supply, FC manufacturing, operations, and maintenance, end of life.	Yes	Yes	Yes	N/A	N/A	Yes	Yes	SimaPro 7.3
Vilbergsson *et al.*, (2023)	1 MW	H2	Local needs	1 kg	Cradle-to-Gate	Yes	Yes	N/A	N/A	N/A	Yes	N/A	ReCiPe
Lee *et al.* (2022)	N/A	H2, MGO & LNG	170 GT Ferry	N/A	Well-to-Tank, Tank-to-Wake & Well-to-Wake	Yes	Yes	Yes	N/A	Yes	N/A	N/A	TRACI 2.1 & GaBi Software
WMU (2023)	N/A	BH_2, GH_2, & BNH_3	Marine Engine Fuel	1 kWh	Well-to-Wank & Tank-to-wake	Yes & GWP (20)	No	No	Yes (All)	N/A	Yes	Yes	GaBi Software
Wang *et al.* (2022)	V-12 4-Stroke Cycle Engine	MGO, LNG, Methanol, Biodiesel & H_2	Super Yacht	1 kg	Well-to-Wake	Yes	Yes	Yes	Yes (All)	N/A	N/A	N/A	Ecoinvent V3.7.1

Authors	Size(s)	Fuel(s)	Application	Functional Unit	System Boundaries	GWP (100)	Acidification	Photochemical Ozone Creation Potential	CO_2, CH_4 & N_2O	Particular Matter	Energy resource demand (kWh)	Material resources demand	LCA Software
Terlouw *et al.*, (2022)	10 tonnes	H2	(PEM) Water Electrolysis	1 kg	Cradle-to-Gate	Yes	N/A	N/A	N/A	N/A	N/A	Yes	Ecoinvent v3.7.1
Desantes *et al.*, (2020)	150 000 km	H2	Vehicle	1 MJ	Well-to-Wheel	Yes	N/A	N/A	Yes (All)	N/A	N/A	N/A	GREET
Zhao & Pedersen (2018)	N/A	H2	Hybrid Electric Vehicle	1 kg	Cradle-to-Grave	Yes	Yes	Yes	N/A	N/A	Yes	Yes	Ecoinvent
Perčić *et al.* (2022)	250 kWh	Battery	Ro-Ro Passenger Ship	Amount of ship emissions over lifetime	Well-to-Pump, Pump-to-Wake & Manufacturing Phase	Yes	N/A	N/A	Yes (All)	N/A	N/A	N/A	GREET
Hwang *et al.* (2020)	N/A	MGO, Natural Gas & H2 (SMR)	12 000 GT coastal Ferry	1.08 x 10_9 MJ	Well-to-Tank, Tank-to-Wake & Well-to-Wake	Yes	Yes	Yes	N/A	Yes	N/A	N/A	TRACI 2.1
Delpierre *et al.*, (2021)	1GW & 100 MW	H2	PEM & AFC	1 kg at 20 bars produced	Cradle-to-Gate	N/A	Yes	Yes	Yes (CO_2)	N/A	N/A	N/A	OpenLCA & Ecoinvent 3.4

Authors	**Size(s)**	**Fuel(s)**	**Application**	**Functional Unit**	**System Boundaries**	**GWP (100)**	**Acidification**	**Photochemical Ozone Creation Potential**	**CO_2, CH_4 & N_2O**	**Particular Matter**	**Energy resource demand (kWh)**	**Material resources demand**	**LCA Software**
Bicer & Dincer (2018)	N/A	H2 & Ammonia	Engine for Sea Transportation Vehicle	1 tonne-kilometre	Well-to-Pump, Pump-to-Hull & Well-to-Haul	Yes	Yes	Yes	N/A	N/A	N/A	N/A	SimaProLCA, Ecoinvent v3.3 & GREET
Chen & Lam (2022)	N/A	H2 & MDE	Tugboat	1 set power system onboard	Manufacturing, Operation, Maintenance, Fuel Production & Distribution	Yes	Yes	Yes	N/A	N/A	N/A	N/A	SimPro & Ecoinvent 3.6
Bicer & Khalid (2020)	N/A	H2, Ammonia & Methanol	SOFC, BOP Stack	1 kWh	Cradle-to-Grave	N/A	N/A	Yes	N/A	Yes	Yes	Yes	ReCiPe 1.8 Midpoint

Authors	Size(s)	Fuel(s)	Application	Functional Unit	System Boundaries	GWP (100)	Acidification	Photochemical Ozone Creation Potential	CO_2, CH_4 & N_2O	Particular Matter	Energy resource demand (kWh)	Material resources demand	LCA Software
Pereira & Coelho (2013)	N/A	H2	Heavy duty vehicle	N/A	Well-to-Pump & Well-to-Wake	Yes	N/A	N/A	Yes	Yes	Yes	N/A	GREET 1.8c, GEMIS & NETPAS
Valente *et al.*, (2016)	N/A	H2 Cases	Mobility & Stationary	N/A	XtoGate, XtoGrave	N/A	N/A	N/A	N/A	N/A	N/A	N/A	GREET
Bhandari & Zapp (2014)	N/A	H2 via SMR (Natural Gas)	Fuel Cell Vehicle (PEM, Alkaline)	1 kg	N/A	Yes	Yes	Yes	Yes	N/A	Yes	N/A	N/A
Guven & Kayalica (2023)	N/A	Lithium Batteries & diesel power	Ferry	N/A	Well-to-Pump, Well-to-Wake & Pump-to-Wake	Yes	N/A	N/A	Yes	Yes	Yes	N/A	GREET
Ghandehariun & Kumar (2016)	40 km pipeline	H2	Wind Power	1 kg	Wind power, H2, compression, water electrolysis and transportation	Yes	Yes	N/A	N/A	N/A	N/A	N/A	N/A

Authors	**Size(s)**	**Fuel(s)**	**Application**	**Functional Unit**	**System Boundaries**	**GWP (100)**	**Acidification**	**Photochemical Ozone Creation Potential**	**CO_2, CH_4 & N_2O**	**Particular Matter**	**Energy resource demand (kWh)**	**Material resources demand**	**LCA Software**
Rillo *et al.* (2017)	1MW & 250kWh	Sewage Biogas	SOFC, ICE & Microturbines	1 kWh	Cradle-to-Gate	Yes	N/A	Yes	N/A	Yes	N/A	Yes	Ecoinvent v2.2, ReCiPe & SimPro v7.3.3
Fernández-Ríos et al., (2022)	N/A	H2	PEMFC, H2 ICE & Diesel ICE	1 kWh	Cradle-to-Grave	Yes	Yes	Yes	N/A	N/A	Yes	Yes	GaBi
Huang *et al.* (2022)	N/A	LNG, Methanol, Ammonia and MGO	Very Large Crude Carrier	Mass (tons) of fuel consumption for a year	Tank-to-Wake & Well-to-Tank	Yes	N/A	N/A	Yes	N/A	N/A	N/A	N/A

Table 3 Life Cycle Analysis Literature

Specifications of the Vessel and Fuel Type (MDO, GH_2 ICE, GH_2 SOFC)

Table 4 Vessel Specifications

Specification	Value	Unit
Deadweight	32771	ton
LOA	112	m
Maximum Speed	15	Knot
Maximum Engine Power	8800	kW
Engine Speed	100	rpm
Life Span	30	years
Fuel Type	MDO	N/A
Operation hours/years	7353.7	hour

Table 4 above details the vessel's specifications to demonstrate the vessel type with its maximum units to assist in understanding the case study. The vessel is a tanker with a maximum speed of 15 knots, a maximum power of 8800 kW, and a horsepower of 7945, equivalent to 5931.2978 kW.

Table 5 Ship Operation Profile

Item	Port	Manoeuvring	Sailing	
Annual operation hours [h]	3443.6	876.1	3034	
Speed [knots]	0	13	14.5	
Engine load [%]	0	76	80	
Percentage [%]	46.83	11.92	41.26	
Engine Power [kW]	0	5931.2978		
SFOC [g/kwh]	0	180.2	180.2	MDO - ICE
	0	64.1	64.1	GH_2 - ICE
	0	49.2	49.2	GH_2 - SOFC
Power SOFC [kW]	0	250* each		
Annual FC [Ton/Year]				
	MDO	GH_2 - ICE	GH_2 - SOFC	
	5054	1798.559	1379.878	

*SOFC required 24 of the 250 power fuel cells to be material replaced every six years.[1]

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[1] *SOFC required 24 of the 250 power of fuel cells that need to be material replaced every 6 years.

Table 5 above reveals the vessel's operation profile, indicating the factor that can determine the costs of the vessel's operation. For instance, as shown in the table, the vessel spends more time at the port to better understand the operations profile. The table above also indicates the annual operational hours of the vessels of 7353,7 hours divided into three parts: port, manoeuvring, and sailing. Furthermore, it provides the annual fuel consumption for MDO, GH_2 ICE, and GH_2 SOFC and the engine power of 5931,2978 kWh.

Table 6 Specification of Fuel Type

Fuel Type	**MDO**	**GH2**	
Capacity (kW)	**5931.2978**		
	ICE	SOFC	ICE
Efficiency (%)	47	61	46.8
LHV (kWh/kg)	11.86	33.3	33.3
Fuel Consumption (g/kWh)	180.2 (for 1 kWh)	49.19	64.12

The fuel specification Table 6 above shows the type of efficiency from hydrogen using solid oxide fuel cells and internal combustion engines as well as marine diesel oil using ICE, as well as low heat value (LHV) of the fuel type. The LHV can assist in identifying the energy density (gravimetric) and volume storage (volumetric) (figure 1). The fuel consumption of each fuel type is indicated using a g/kWh unit.

Conclusion

The chapter provided information on South Africa and its interest in green hydrogen production. The study further outlined the environmental impact and economic evaluation, including details on wind production and the calculations of capital and operation costs of wind production. Qualitative research was employed but presented in a quantified format as a table outlining the literature reviewed in the study. Furthermore, the chapter provided the vessel specification and limitations.

The following chapter will discuss the results of data collected and analyzed from the previous chapter.

Chapter 4: Data Presentation and Results Analysis

Introduction

The research investigated green hydrogen's environmental impact and economic evaluation and compared it with marine diesel oil using energy conversion technology and engines. The findings were obtained from the data collected using software on wind production and economic performance and vessel propulsion tools (engine and solid oxide fuel cells). The data presented, interpreted, and analyzed is extracted from the software. Furthermore, the structure of this chapter is as follows: offshore wind power, life cycle assessment, life cycle cost assessment, and interpretation.

Offshore Wind Power Output

The wind resource of South Africa is presented utilizing various characteristics such as wind power, wind speed, and accumulated energy. The data collected and presented in the graphs indicate the abundance of wind resources in South Africa Saldanha Bay Port. Figure 7 below shows that wind is a resource feasible for hydrogen production on the site. The mean wind speed is rated at 8.7m/s, indicating that the offshore area is windy. South Africa is best suited for green hydrogen production, as Table 7 below proves, with such high speed and wind power over two years from one wind turbine. The wind turbine cut-off power is 4500W, and production is approximately 20000000 kWh.

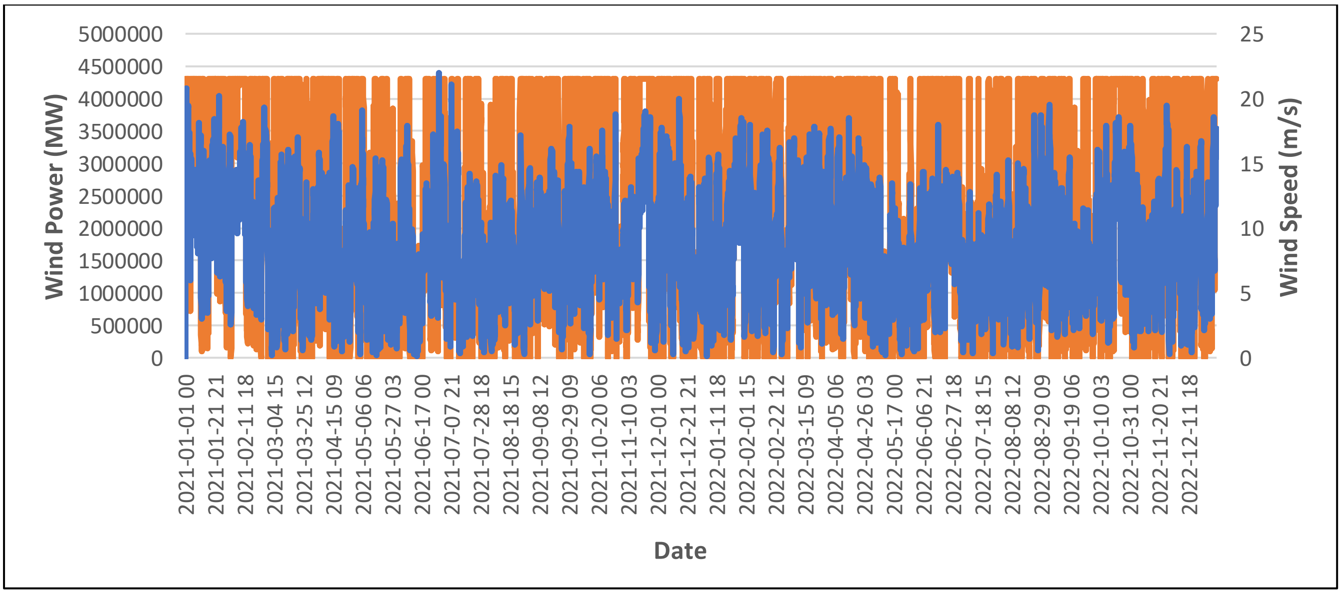

Figure 7 2021-2022 Capacity Factor of Wind Speed and Power

Figure 8 below indicates the cumulative energy amount in kWh from 2021 to 2022. This shows a slightly constant cumulative power per second each day. Figure 10 demonstrates that hydrogen energy will best be the suited area for production in South Africa at the Saldanha Bay offshore wind farm. The diameter is 120, with a *Cp* of 0.51 for two years with a cumulative energy of 40 000 000 000kWh. Even though such an amount of power indicates energy generation, which stipulates that if the *Cp* is high, more electricity will be generated.

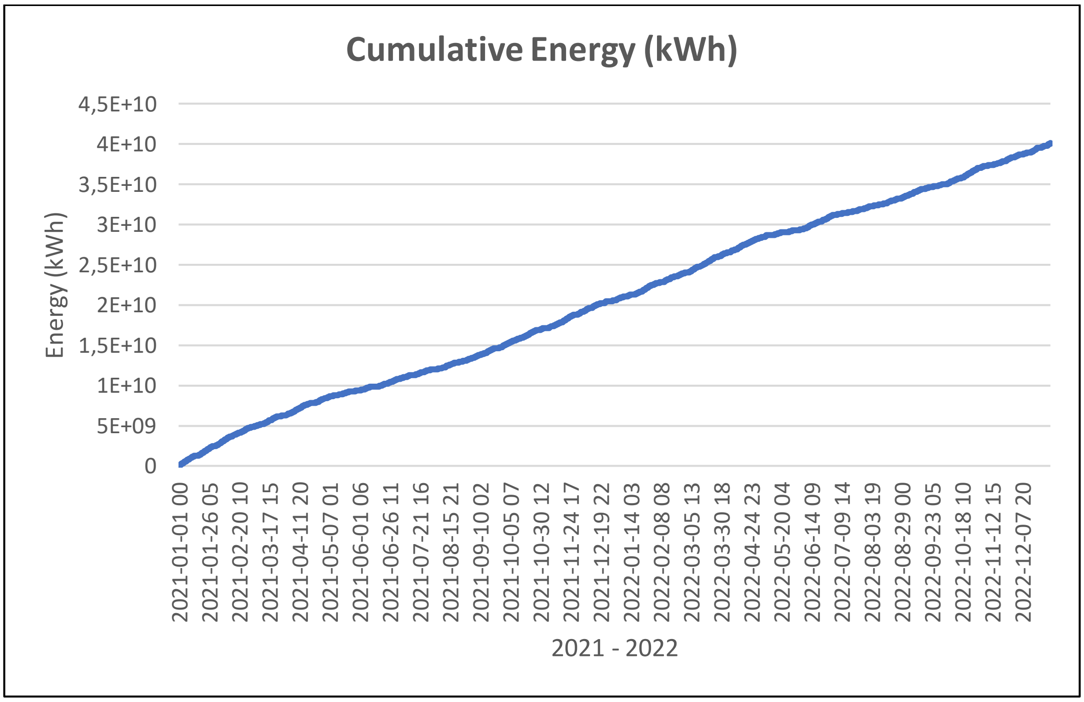

Figure 8 Cumulative Energy, 2021-2022

Table 7 below provides the specification of offshore wind production of hydrogen (354 735,7 kg) per annum. It provides items such as the cost of hydrogen, as stated in IRENA (2022). One kg of hydrogen is $12.50, with an average amount between $10 and $15 (IEA, 2022).

Table 7 indicates the Offshore Wind Production Specifications

Item	**Value**	**Unit**
Turbine (power)	4.5 MW	MW
	4500	kWh
Turbine (produces)	20 GWT	GWT
	20000000	kWh
GH_2	1	kg
	56,38	kWh

GH_2 (annual production)		354 735,7	kg
GH_2 price in IRENA	$	12,50	$

The economic viability of hydrogen production through electricity generation was examined. Table 8 below indicates that the capital cost of one wind turbine to produce hydrogen is $15 574 500, with operational costs of close to 1.7 million/USD. An income of $2 million was generated from the wind turbine. $ 354,735.72 is produced annually and could increase depending on the interest rate, currently at 7.19%. The hydrogen costs are initially dependent on the amount of production; therefore, in this case, the site's selling price, such as Saldanha Bay, can be lower as the turbine produces adequate wind.

Table 8 Offshore Wind Production of Hydrogen LCoH

Offshore Wind Production of Hydrogen		
CAPEX	$ 15,574,500.00	
OPEX	$ 1,620,000.00	
Generated Revenue	$ 354,735.72	GH_2 Produced
	$ 4,434,196.52	Sold GH_2
Income	$ 2,814,196.52	

The operation expenditures of *LCoH* entail an essential cost of the system as it entails maintenance, cabling, labor costs, and environmental issues. Other maintenance issues include enough skilled individuals to assist in maintaining the offshore wind turbines and the system.

Figure 9, below, indicates the *NPV, IRR,* and discounted rate with a 5.53-year payback period. This is a good investment; therefore, it could yield good returns if hydrogen is produced locally. Considering the lifespan of the wind turbine of 30 years, this investment could generate substantial amounts of hydrogen not only for the maritime industry but also for other industries and household consumption for electricity generation, as South Africa has been experiencing power cuts as the national grid is failing to supply electricity. Furthermore, the GH_2 production will also create direct and indirect jobs. This investment is favorable for supply in large amounts, considering the average of 8.7m/s. However, the risk of assets presented at a discounted rate of 7.19% as a baseline for offshore wind hydrogen production has uncertainties. The *LCoH* is still developing, especially in developing countries; therefore, it will impact capital costs and the market decline of renewable energy production of hydrogen (IRENA, 2023).

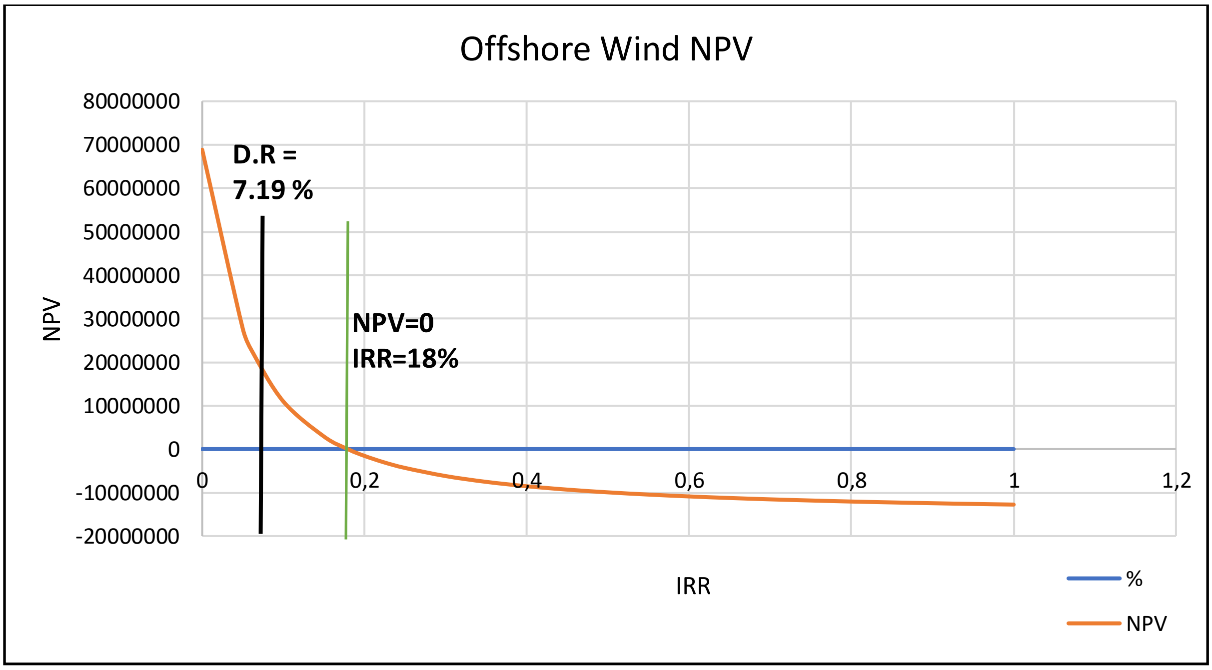

Figure 9 Offshore Wind Production of Hydrogen Net Present Value

The production of wind-based hydrogen is essential for reducing GHG emissions and assisting in decarbonizing especially the maritime industry. However, due to the abundance of hydrogen production in Saldanha Bay and the yields of suitable investments from Figures 7 and 9, Tables 7 and 8). Adopting green hydrogen production through wind could be critical in speeding up the decarbonization pathway.

Even though there are challenges associated with offshore wind turbine operation and maintenance, which need to be included in the data due to lack of data, it still indicates that the payback period will still be low, especially if more turnover is included. However, with increased development comes environmental issues such as $kgCO_2eq/kWh$ of 0.8 GWP100 (GaBi database).

The section presented the offshore wind power output from wind power and windspeed to indicate the wind resources in the area. Moreover, the NPV, IRR, and payback period are shown in Figure 9 and Table 8. This has indicated the abundant wind resources and how much the investment and payback period can cost for one large wind turbine. The following section will explore life cycle impacts Assessment using GaBi, Ecoinvent, and IMO LCA guidelines.

Life Cycle Assessment

The LCA goal and scope is to assess the environmental burdens of MDO and GH_2 on both ICE and SOFC. ICE is fueled with MDO and GH_2. The fuel cell technology requires 250kW times 24 to equal the ICE at 5931.2978 kWh.

Life Cycle Impact Assessment

The potential environmental effects are evaluated from both system boundaries of MDO and H_2 using both IPCC (GaBi and Ecoinvent) and IMO guidelines.

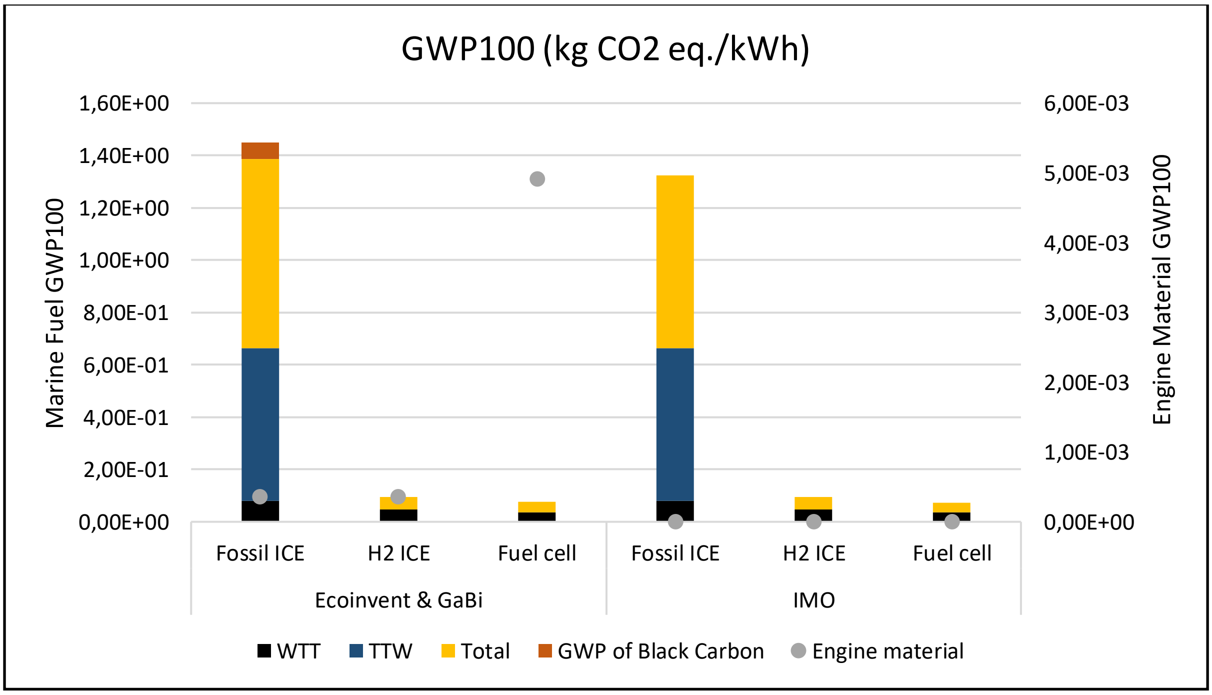

Figure 10 GWP100 (kg CO2 eq./kWh) of Life cycle Assessment of Marine Diesel Oil and Green Hydrogen and Engine Material

Figure 10 above illustrates the LCA of environmental impacts based on IMO, GaBi, and Ecoinvent (IPCC). The system boundary of WTT and TTW using IMO LCA and IPCC (2023). The illustration also indicates the material of Solid Oxide Fuel Cells and marine engines accompanied by black carbon, which is part of GaBi and Ecoinvent (IPCC). The two LCAs carried out here are those of the IMO and IPCC, as IMO included CO_2, CH_4, and N_2O, As opposed to IPCC, which incorporates all 264 - GWP100 emissions. The difference is that IMO excluded the other emissions such as SOx, VOC, water depletion, eutrophication, Ozone depletion, and black carbon. However, the IPCC has included those. The graph Figure 10 above notes the standing out data of how the IMO and IPCC have almost the same results. However, they have minor differences even though other emissions were not included.

Scenario 1: Fossil ICE (MDO)

The emissions associated with fossil ICE at the WTT system boundary show a difference of 0.000127 kgCO_2eq./kWh between the IPCC (GaBi and Ecoinvent), which reports the highest emissions at 0.0818 kgCO_2eq./kWh, and the IMO framework. These variations are attributed to the additional emissions considered in the GWP100 in the IPCC framework compared to the three emissions included in the IMO LCA guidelines.

Figure 10 highlights the highest emissions during the TTW phase for both IMO and IPCC, reaching 0.58 kgCO_2eq./kWh for the MDO used in ICE. TTW emissions are high due to the operational phase of fuel utilization when combustion occurs for propulsion, which releases more emissions into the atmosphere.

Scenario 2: H_2 ICE

The hydrogen-fuelled ICE emissions differ between the IMO and IPCC frameworks, with IMO showing higher emissions at 0.0465 kgCO_2eq./kWh. However, it's essential to consider the TTW phase of ICE, as hydrogen emissions are not associated. This is because GH_2 is a clean fuel source, evident in the lack of emissions during operation.

Regarding hydrogen-fueled ICE, there is only a minimal difference of 0.00012 kgCO_2eq./kWh for the WTT phase between institutions. The emissions for ICE were measured at 0.356 kgCO_2eq./kWh (as seen in Table 9). When H_2 is injected into the same engine as fossil fuel, the results for H_2 ICE remain consistent between IMO and IPCC, as there are no additional emissions generated during operation in either case.

Scenario 3: GH_2 SOFC

The GWP100 emissions associated with fuel cells under the system boundary of WTT in the IMO framework are notably higher at 0.0358 kgCO_2eq./kWh, as opposed to the emissions in the IPCC framework, which are lower at 0.0001 kgCO_2eq./kWh. This significant difference can be attributed to fuel cell materials playing a more substantial role in GWP100 emissions than ICE.

The increased emissions from fuel cells may be due to the need for frequent replacements of fuel cell stacks every six years over a 30-year lifespan. The fuel cell inventory is calculated based on 250 kWh of fuel cells, which was then multiplied by 24 to reach the same power output as 5931.27 kWh. Consequently, the GWP100 emissions for fuel cells amount to 4.15 kgCO_2eq./kWh. This is primarily due to the high electricity demand associated with fuel cell manufacturing and operational processes. It's important to note that hydrogen generates no emissions as a fuel source, as indicated in the previous figure. However, the need for more frequent material replacements, driven by the fuel cell stacks, increases emissions over time.

Black Carbon

In contrast, as shown in Figure 10, the IPCC considers Black Carbon (BC) emissions, whereas the IMO excludes BC from its calculations. BC emissions amount to 0.0616 kgCO_2eq./kWh when fossil fuel-based fuels are used, whereas no emissions are associated with H_2. BC is notorious for being practically invisible except when it settles on snow, which diminishes the snow's albedo and adversely affects local air quality. Although fishing vessels are often regarded as the primary contributors to BC emissions, it's essential to note that international shipping also plays a role in emitting BC and affecting the Arctic region, as observed by Zhang et al. (2019).

The subsequent section delves into the Global Warming Potential (GWP100) emissions of engine materials for both ICE and SOFC over the 30-year lifespan of the vessel.

Table 9 GWP100 of Engine Material.

GWP100 of Engine Material		
Energy density	kg steel/kWh	2.54E-04
GWP of steel	kg CO_2 eq./ 1 kwh of steel	0.4
GWP of engine material	kg CO_2 eq./kWh	3.56E-01

Table 9 provides the GWP100 associated with ICE materials in kWh. The energy density of the ICE material is 0.00025, while steel has a significantly higher emission value at 0.4, resulting in an overall emission factor of 0.356 kgCO_2eq./kWh for the entire material.

In the study, ICE assumed the same emission factors for GH_2 fuel and MDO, and these emissions are considered as one-time emissions unless maintenance necessitates the replacement of a component within the engine.

The materials for fuel cells encompass the balance of plant (BOP), anaerobic components, and the fuel cell stack itself. Rillo et al. (2017) adopted the material inventory for fuel cells.

Table 10 SOFC GWP100 of Materials Adopted from Rillo et al. (2017)

SOFC GWP100 of Materials		
NiO	kg CO_2 eq./1 kWh	7.61E-04
Stainless steel	kg CO_2 eq./1 kWh	1.11E-03
Reinforcing steel	kg CO_2 eq./1 kWh	3.04E-03
Total	***kg CO_2 eq./1 kWh***	***4.91E-03***

The results presented in Table 10 relate to the Global Warming Potential (GWP100) associated with the materials used in Solid Oxide Fuel Cells (SOFC) per 1 kWh of capacity of one fuel cell. Specifically, the emissions are broken down as 0.000761 kg CO2 equivalent per kWh from NiO, 0.00111 from stainless steel, and 0.03 from reinforcing steel. These emissions associated with SOFC are categorized according to these three materials and are accompanied by yearly maintenance requirements. It's important to note that SOFCs have a lifespan of six years, which necessitates replacement every six years, resulting in four replacements over their operational lifetime (considering the initial installation with the vessel). Furthermore, the data presented pertains to a single fuel cell. To achieve the same power output of 5931 kWh, a total of 24 fuel cells is required. This is because each fuel cell, as adopted from Rillo *et al.* (2019), has a power capacity of 250 kWh.

This information underscores that SOFCs have a high maintenance requirement and demand additional labour and maintenance, especially concerning the anode off-gas recirculation. The emissions related to SOFCs are primarily generated during the manufacturing phase, which involves high electricity consumption (Rillo *et al.*, 2017).

Table 11 Energy Efficiency of Green Hydrogen on Internal Combustion Engine and Solid Oxide Fuel Cell

	Energy Efficiency (kWh)	
	GH_2 ICE	**GH_2 SOFC**
Annual	639987451,7	491006766,3
30 years	19199623552	14730202988

The data presented in Table 11 above provides insights into the annual and 30-year energy efficiency of GH_2 ICE and SOFC. The results indicate that SOFC consumes less energy to accomplish the same tasks (propulsion) both on an annual basis and over a three-decade period when compared to GH_2 ICE. In contrast, GH_2 ICE demands more energy than SOFC for both the annual and 30-year timeframes.

In summary, GH_2 SOFC demonstrates lower energy consumption over the course of a year and three decades. It's also important to highlight that GH_2 ICE requires approximately 23.3% more energy to achieve the same level of efficiency as SOFC.

Life Cycle Cost Assessment

The life cycle cost analysis represents the economic performances of MDO, GH_2 ICE, and GH_2 SOFC. It further analyzes the carbon credit and net present value (operations and maintenance) of the three propulsion systems, including IRR and PBP.

Manufacturing:

Table 12 Construction costs (Using Power) (5931 kWh)

Construction Using Power (5931 kW)	
ICE	**SOFC**
$ 8,499,549.75	$ 11,152,386.75

Table 12, displayed above, outlines the construction costs for both SOFC and ICE. It is noteworthy that manufacturing ICE is considerably more cost-effective due to the mature technology and established industry reputation than hydrogen fuel cells powered by GH_2. The costs associated with hydrogen as a maritime fuel remain elevated, reflecting the novelty of this technology. Investing in it may entail risks, mainly because GH_2 SOFC is still in its early developmental stages.

Additionally, it's essential to consider the requirements for accommodating a 5931.27 kWh power capacity, which necessitates using 24 fuel cells, each with an equivalent rating of 250 kWh, matching the vessel's horsepower.

Operations and Maintenance

Table 13 Total Fuel Consumption and Costs

Total Fuel Consumption & Costs						
	1st year			**30 years**		
Fuel Type	**ton/year**	Costs	Difference	**ton/30**	Costs	Difference
MDO	5,055	$ 3,977,891.50	-	151,635	$ 119,336,745.00	-
GH_2 ICE	1,799	$ 22,482,083.33	-$18,504,191.83	53,957	$ 674,462,500.00	$ -555,125,755.00
GH_2 SOFC	1,380	$ 17,248,333.33	-$13,270,441.83	41,396	$ 517,450,000.00	$ -398,113,255.00

*Assuming that green hydrogen costs 12.5 $/kg (IRENA, 2021) and MDO costs 787 ($/ton) (Dan-Bunkering, 2023)[2]

The total fuel consumption and costs are presented in Table 13. Approximately 5055 tons of MDO are projected to cost around 3.9 million/USD in the first year, and over 30 years, the cost accumulates to 119 million USD. This is a more cost-effective option than GH_2 ICE, which incurs annual costs of 22.4 million/USD, resulting in a 30-year total of 674.4 million/USD, representing a substantial difference of 555 million/USD. GH_2 SOFC is also notably distinct, with an initial cost of 13.2 million/USD in the first year and a 30-year total of 398.1 million/USD, signifying a significant difference from MDO.

The table underlines that MDO is a cost-effective choice in contrast to GH_2. Despite its lower energy density compared to MDO, the pricing structure for GH_2 remains relatively high.

Carbon Credit

Table 14 Carbon Credit for MDO per year

MDO Carbon Credit (per ton)				
CO_2	CH_4	N_2O	1st year	30 years
$1 458 425,43	$227,45	$81,88	$1 458 734,77	$ 43 762 042,96

*$90 tCO_2 (IEA, 2022)[3]

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[2] *Assuming that green hydrogen costs 12.5 $/kg (IRENA, 2021) and MDO costs 787 ($/ton) (Dan Bunkering, 2023)

[3] *$90 tCO_2 (IEA, 2022)

Table 14, presented above, details the yearly carbon credits calculated following the guidelines set by the IMO. These figures are determined by multiplying the annual fuel consumption of MDO by the appropriate emission factor, which is then multiplied by the applicable carbon credit for the specific geographic location, in this case, South Africa at $90 (IEA, 2022). In the initial year, the revenue generated from MDO amounts to 1.5 million/USD. At the same time, over a three-decade period, it accumulates to 43.7 million/USD based on the emissions associated with MDO. The carbon credit amount is calculated by adding the carbon credit to the fuel consumption cost of MDO. It's worth noting that GH_2 is considered a clean fuel, and therefore, carbon credit does not apply in this context.

Table 15 Operation and Carbon Credit for a year and 30 years, including the differences

Carbon Credit (Inclusive)				
	Year	**Difference**	**30 Years**	**Differences**
MDO	$ 5,436,626.27	$ -	$ 163,098,787.96	$ -
GH_2 ICE	$ 22,482,083.33	$ -17,045,457.07	$ 674,462,500.00	$ -511,363,712.04
GH_2 SOFC	$ 17,248,333.33	$ -11,811,707.07	$ 517,450,000.00	$ -354,351,212.04

The table above incorporates carbon credits for the annual and 30-year durations in all three scenarios. Initially, MDO was selected as the baseline for fuel consumption costs, including carbon credits. This inclusion increases operational costs. However, it's important to note that the difference remains below 22 million/USD annually and 674 million/USD over 30 years when comparing MDO to hydrogen in both ICE and SOFC technologies.

This table underscores that even after factoring in the carbon credit for every ton of MDO, the overall cost remains notably lower when compared to hydrogen, whether in the context of internal combustion engines (ICE) or solid oxide fuel cells (SOFC).

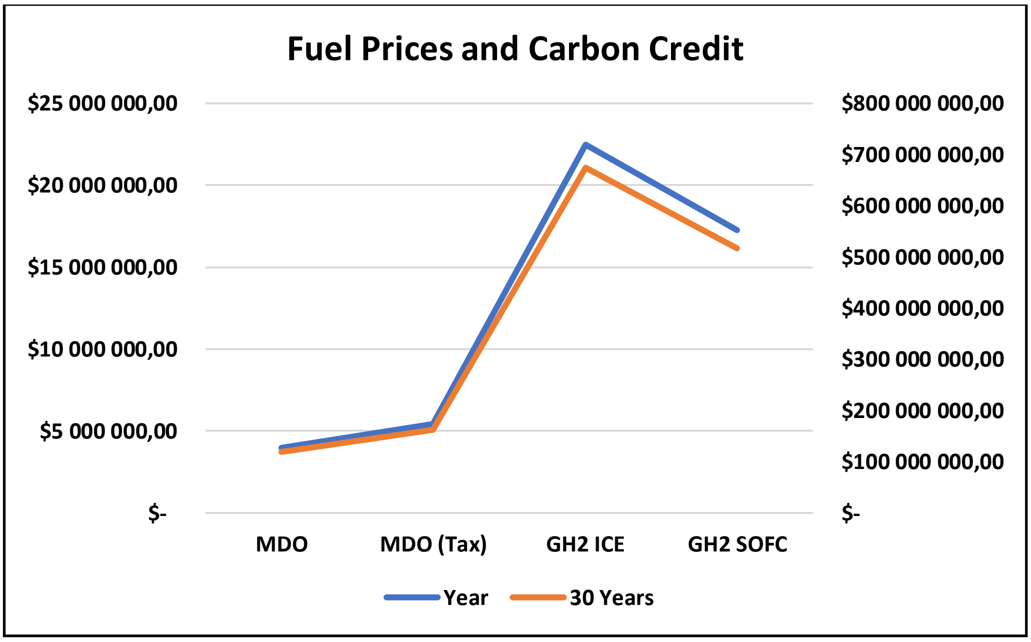

Figure 11 Fuel Prices and Carbon Credit

The graph in Figure 11, displayed above, illustrates MDO, GH2 ICE, and GH2 SOFC fuel prices, with MDO factoring in carbon credits. This graph emphasizes that it remains the most cost-effective option even with MDO priced at $90 in South Africa (IEA, 2022). Furthermore, it underscores the cost-intensive nature of green hydrogen. However, GH_2 SOFC offers a more economically viable alternative than GH_2 ICE, assuming the same ICE technology is used for both MDO and hydrogen (GH_2 ICE).

It is important to note that this analysis needs to account for potential future trends in hydrogen costs. There is potential for hydrogen prices to decrease over time, as indicated by research from IRENA (2020). This trend is similar to the reduction in the price of solar panels over the past 13 years (IRENA, 2023). Therefore, the current cost comparison may not fully represent the cumulative cost pattern, given the potential for future cost reductions in hydrogen technology.

Table 16 Carbon Credit

Savings of Hydrogen to Minimise Costs by Subtracting Carbon Credit			
	GH_2 ICE	**GH_2 SOFC**	**MDO**
1st year	$ 21 023 348,57	$ 15 789 598,57	$ 5436626,265
30 years	$ 630 700 457,04	$ 473 687 957,04	$ 517450000

Table 16, displayed above, outlines the estimated annual and 30-year costs associated with various propulsion systems, specifically MDO, GH_2 SOFC, and GH_2 ICE. The reductions in prices for GH_2 ICE and SOFC are a deliberate aspect of the study, highlighting the potential cost savings achievable when employing hydrogen as a maritime fuel.

In order to measure these savings effectively for GH_2 propulsion, both on an annual and 30-year basis, the carbon credit price has been factored in. This adjustment is crucial for determining the extent to which GH_2 ICE or SOFC could yield cost savings. However, it's essential to recognize that these outcomes are contingent on the assumption that the carbon price remains constant.

Net Value of GH_2 ICE and SOFC

Table 17 Net Value of GH_2 ICE and SOFC

Annual	
Net Value (GH_2 ICE)	**Net Value (SOFC)**
$ 14 127 987,54	$ 8 894 237,54
30 years	
$ 423 839 626,11	$ 266 827 126,11

The data in Table 17 depicts the annual net values for two propulsion systems, GH_2 ICE and GH_2 SOFC, over 30 years. These values encompass the financial benefits associated with each propulsion system.

GH2 ICE is projected to yield an annual return of approximately $14 million in the initial year, while SOFC is expected to generate around $8.8 million. Over the course of 30 years, these values are anticipated to increase. However, it's noteworthy that the GH_2 ICE propulsion system is expected to remain more costly than the GH_2 SOFC system.

NPV Profile of GH_2 on ICE, SOFC

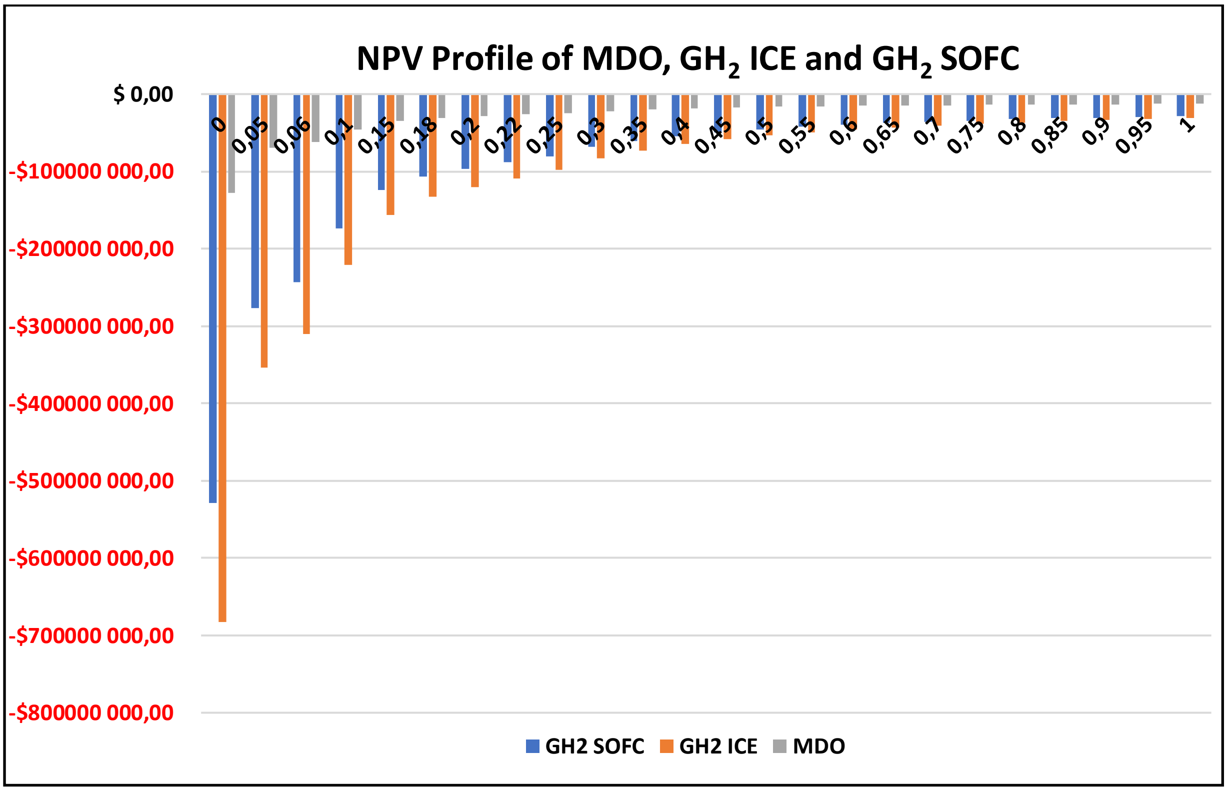

Figure 12 NPV Profile of Marine Diesel Engine, Green Hydrogen on Internal Combustion Engine, and Solid Oxide Fuel Cells

Figure 13 above illustrates the Net Present Value Profile of MDO, GH_2 ICE, and GH_2 SOFC. The graph shows an unfavourable financial basis for the propulsion system, indicating that the propulsion system costs outweigh the expected benefits. However, in some cases, when assessing NPV in relation to fuel consumption, a negative NPV is expected or observed, signifying that the costs surpass the benefits and savings. Consumption represents an ongoing expenditure that continues over time. The negative NPV signifies recurring expenses over the 30-year period. The NPV profile reveals that all fuels yield negative values. Nonetheless, GH_2 ICE incurs the highest costs among the fuels, followed by GH_2 SOFC, while MDO is the most affordable option compared to GH_2.

SWOT Analysis

Strengths

- Increased funding availability and aligning South Africa's diversification goals
- Effective international partnerships
- Abundant, affordable wind energy
- Strong potential for production of green hydrogen
- Established infrastructure for exporting hydrogen and derivative
- Abundance of renewable energy, particularly wind power
- Capability for storing hydrogen with high density
- Ideal location for exports
- Proven expertise in energy trading

Weaknesses

- Heavy reliance on coal for energy
- Elevated expenses for transportation and storage
- Limited involvement of private companies
- Low domestic demand
- Challenges with laws and regulations
- Underdeveloped and energy intensive electrolyzer technology
- Lack of a comprehensive hydrogen strategy in the South Africa
- No feasible national plan for hydrogen energy Roadmap
- Water scarcity Country
- High production expenses

Opportunities

- Reducing greenhouse gas emissions (GHG) and other environmental impacts
- Opening up opportunities in export markets
- Integrating hydrogen into the circular carbon economy
- Expanding the range of companies engaged in the energy sector
- High potential for developing and using electrolyzer technology locally
- Attracting foreign investments
- Fulfilling local energy demands
- Job creation

Threats

- The nation is stuck in an old coal-dependent position and is slow to adapt to the transition.
- Lack of an established carbon pricing system or a clear business model.
- Other nations are progressing more rapidly in capacity building and securing export markets.
- Uneven distribution of potential might lead the country to compete rather than cooperate with neighbouring countries such as Namibia in the SADC region.
- Safety risk and public acceptance

Figure 13 SWOT analysis factors of the hydrogen economy in South Africa

Offshore Wind Power Output

The overview on the potential of hydrogen production through offshore wind energy in South Africa, Saldanha Bay Port. The discussion touched on various aspects, such as wind resource characteristics, economic considerations, and environmental impacts.

The results chapter emphasizes the mean value of 8.7m/s wind speed, indicating a substantial wind resource in the area. This is crucial for an offshore wind project, as a higher wind speed produces tremendous energy (Abadie & Chamorro, 2023). Turbines further exemplify this in high-wind-speed areas, producing low-cost energy primarily determined by resource availability. The suitability of Saldanha Bay for green hydrogen production is rooted in its high wind power and speed. Therefore, Saldanha Bay is a promising location for exploring green hydrogen production through offshore wind power—the wind turbine specifications point towards efficient energy conversion and high electricity generation for maritime transportation.

The level of hydrogen production significantly influences the economic analysis. It is assumed that the large turbine size will result in significant production, so it is essential to consider resource availability. The country's electricity cost can also influence the cost of hydrogen production. The information regarding operational, maintenance, and capital costs of hydrogen production through wind turbines is provided, with a payback period of 5.53 years and a positive NPV and IRR, indicating an attractive financial investment on the offshore wind turbine for green hydrogen production within the maritime sector.

The challenges related to offshore wind power, specifically operations and maintenance, are acknowledged but not included in the results due to inadequate information. However, the potential for reducing GHG emissions by decreasing dependency on fossil fuel-based hydrogen production is high, which can be particularly beneficial in the maritime sector for reducing feedstock emissions and fostering environmental sustainability.

Life Cycle Assessment (LCA)

The life cycle assessment discussion centers around three propulsion system scenarios: MDO, GH_2 ICE, and GH_2 SOFC. The analysis considers the potential environmental impacts within the system boundaries, which are defined by the guidelines set forth by the IMO and IPCC.

The IMO and IPCC LCA Framework Guidelines

The guidelines established by the IMO serve distinct purposes. They primarily focus on evaluating the environmental impacts of ships and shipping activities, including greenhouse gases (GHGs) and other pollutants. These guidelines employ a range of emission factors, a choice driven by the IMO's continued reliance on the emission factors from the previous IPCC report (AR5), to ensure continuity and consistency (IMO, 2020).

The IMO's guidelines support policymaking within the maritime industry, particularly concerning emission reduction, pollution control, and fuel efficiency. In doing so, the primary emphasis is placed on three critical emissions: N_2O, CO_2, and CH_4, which are deemed a priority for the IMO's decarbonization efforts. There is a notable disparity when comparing emissions, assuming that engine material data is used in the IPCC but not in the IMO calculations. This difference equates to 5.67 kgCO_2eq./kWh for the IPCC and a much lower figure of 0.7 kgCO_2eq./kWh for the IMO.

In contrast, the IPCC takes a broader approach, encompassing many sectors and activities beyond the maritime industry. It incorporates all 264 GWP100 emissions to address emissions assessment in various contexts. The framework of the IPCC is concerned with quantifying GHG emissions and mitigating the global temperature increase, particularly to limit the rise to 1.5°C. Consequently, this approach includes all GWP100 emissions and employs a generalized method for data collection and emissions factors applicable across industries. The IPCC primarily focuses on reporting and assessing global and national GHG inventories and is heavily influenced by international agreements such as the Kyoto Protocol and the Paris Agreement.

Scenario 1: Fossil ICE (MDO)

The GWP100 results from both institutions reveal a significant variation in kgCO_2 eq./kWh emissions when using MDO in the shipping industry. The differences in the IPCC emissions can be attributed to the additional gases that the IMO has excluded in the GWP100 assessment. It's worth noting that both frameworks indicate a high emission level of 0.58 kgCO_2 eq./kWh during the TTW phase, primarily due to fossil fuel combustion for propulsion. This value closely aligns with the figures used by other authors on GWP100 assessments, such as Gilbert *et al.* (2020), Fernandez-Rio *et al.* (2022), and Percic *et al.* (2020).

The variability in TTW emissions arises from factors such as the operational hours of the ships during manoeuvring and sailing, as well as the engine load, which significantly influences fuel consumption (Guven & Kayalica, 2023).

Scenario 2: GH_2 ICE

An intriguing trend became apparent when examining the transition to GH_2 ICE. Within this scenario, the emissions calculated using the IMO framework tend to be higher than those from the IPCC. This observation suggests that GH_2 is a cleaner alternative fuel associated with reduced emissions. Notably, a noteworthy point is the complete absence of emissions during the TTW phase when using GH_2, which underscores the cleanliness of this fuel source (Figure 10). Moreover, it's worth mentioning that emissions remain consistent between the IMO and IPCC, even when hydrogen is co-injected into the same engines alongside fossil fuel (MDO).

Scenario 3: GH_2 SOFC

The GH_2 SOFC noteworthy variation in emission between IPCC and IMO. IMO indicates high emissions of WTT, mainly related to the material used on SOFC and the intensive electricity required during manufacturing. In addition, the need for frequent replacement every year for minor maintenance and every six years for the whole fuel cell stacks resulted in higher emissions over the three decades of the vessel's life span. However, if the fuel cells can be produced to sustain for the longest time, i.e., 30 years, it would require minimizing the temperature, which can improve longevity but impact efficiency. Therefore, research and development are required to develop innovative solutions from a multidisciplinary approach to manufacture fuel cells that last longer and still have the same efficiency. In addition, it is an environmentally friendly and recyclable material to assist in reducing emissions for the lifecycle of the materials.

The GH_2 SOFC (Solid Oxide Fuel Cell) reveals a notable disparity in emissions between the IPCC and IMO assessments. The IMO framework points to elevated emissions during the WTT phase, primarily associated with the materials used in SOFC construction and the substantial electricity demand during manufacturing (Rillo *et al.,* 2017). Additionally, the need for frequent replacements, with minor maintenance required annually and complete fuel cell stack replacement every six years, contributes to higher emissions over the three-decade lifespan of the vessel.

However, if fuel cells can be engineered for extended durability, such as a lifespan of 30 years, it would necessitate lowering operating temperatures, which can enhance longevity but might affect efficiency due to high temperatures (Sundén, 2019). Consequently, research and development efforts are imperative to devise innovative, multidisciplinary solutions for manufacturing fuel cells that can endure extended periods while maintaining the same efficiency level. Furthermore, it's crucial to explore the use of environmentally friendly and recyclable materials to mitigate emissions over the material's lifecycle.

Black Carbon

The IMO framework does not account for the environmental impact of Black Carbon (BC) as an emission, whereas the IPCC includes it. BC emissions were observed (figure 10) with 0,0616 kgCO_2eq./kWh concerning fossil fuel-based fuels, such as MDO, contributes to reduced snow albedo and poses local air quality concerns in the Arctic region (Rweileh & Irveby, 2019). Therefore, addressing BC emissions is crucial, especially within the maritime sector. Even though BC is considered to have a relatively short climate life, it still has environmental impacts on flora and fauna and human health, resulting in social costs.

Furthermore, BC's impact on the usage of MDO in the TTW phase is primarily due to its light-absorbing properties. BC has a dark colour on its surface, which makes it capable of attracting sunlight and accelerating the melting of the cryosphere, ultimately leading to glacier discharge (Kang *et al.*, 2020).

Material Emissions

The material analysis extended the GWP100 to cover 30 years of emissions, with steel emerging as the predominant contributor to emissions. On the other hand, SOFC exhibited notable emissions during the manufacturing phase, mainly owing to frequent material replacements (6 years) and electricity-intensive processes. In the case of ICE, their manufacture must be adapted to accommodate alternative fuels such as GH_2 in order to enhance energy efficiency.

South Africa, a country rich in various minerals required for fuel cell manufacturing, has the potential to accelerate the development of the industry, particularly to support GH_2 ICE and SOFC technology.

Energy Efficiency

In assessing the energy efficiency of both GH_2 ICE and SOFC propulsion systems over 30 years, the results indicate that SOFC demonstrates higher efficiency, with a 46.8% consumption rate compared to ICE. This suggests that fuel cells have the potential to save more fuel when compared to ICE, as lower efficiency implies higher fuel consumption. Consequently, more GH_2 would be required for ICE compared to SOFC.

Consequently, GH2 ICE would require more frequent bunkering and increased storage capacity compared to SOFC. This may pose challenges for businesses in the maritime sector, particularly shipowners looking to maximize profits. However, this situation highlights the necessity for continued research and development efforts.

The findings suggest that SOFC energy conversion technology presents a more efficient and sustainable propulsion option, extending its advantages over GH_2 ICE. This alignment to reduce energy consumption and emissions in pursuing a net-zero maritime industry underscores the significance of pursuing SOFC technology.

Life Cycle Cost Assessment

The cost analysis presented in Table 13 highlights that ICE technology is more established and cost-effective, mainly due to its extensive use in the maritime industry. In contrast, SOFC technology is relatively new and perceived as risky regarding investments. This highlights the financial challenges associated with adopting emerging technologies in the maritime sector.

Table 13 also provides a comparison of fuel consumption and costs among different propulsion systems. MDO is cost-effective because of its reasonable fuel prices and lower initial costs. However, both GH_2 ICE and SOFC show higher annual and three-decade costs. This suggests that, although GH_2 is considered a cleaner energy source, the cost structure proves less financially attractive than MDO. MDO's appealing pricing can be attributed to it being in the tertiary stage of fuel with a competitive market, with producers acting as price takers, contrasting GH_2, where producers have more control over pricing due to its limited acceptance. These cost differences are pivotal in the industry's decision-making process when evaluating propulsion system options.

Table 4 introduces the concept of carbon credits and the implications for operating costs. MDO benefits from carbon credits due to its emissions, whereas GH_2 does not, as it's considered a cleaner alternative. Even with the inclusion of carbon credits, MDO has a financial advantage due to its lower cost profile. This underscores the potential economic incentive for adopting cleaner propulsion technologies that benefit the environment.

As shown in Figure 11, fuel prices reflect the higher costs of GH_2 compared to MDO. In addition, GH_2 SOFC exhibits better cost structures compared to GH_2 ICE. This may be influenced by the efficiency (0.468) of ICE and the energy density (57 W/kg) of ICE, which are not designed for retrofitting GH_2 ICE values. This suggests an advantage of using SOFC technology for GH_2 propulsion. However, it's important to note that while the figure indicates a linear trend, fuel prices can experience fluctuations or cost reductions over time (IRENA, 2022), and this assumption assumes linear fuel prices for the vessel's entire 30-year lifespan.

Figure 13 illustrates the NPV profiles of the three propulsion systems over 30 years. Due to ongoing expenses related to fuel consumption and operating costs, all NPVs are negative. This is common in scenarios where recurring expenditures outweigh immediate benefits. GH_2 ICE displays the highest prices, followed by SOFC, with MDO as the more favourable option.

The type of NPV presented, negative NPV, doesn't generate income but is associated with social benefits. Reducing environmental impacts and improving air quality, such as addressing emissions of BC, can alleviate health-related issues, potentially reducing incidents of death, terminal illness, or hospitalization (Kang *et al.*, 2020). Despite having a negative NPV and an Internal Rate of Return (IRR) of less than 0, the project can be considered a social benefit. Therefore, including carbon credits to assess the social benefits is essential. By adopting cleaner propulsion systems, such as GH_2 ICE and SOFC, across a significant portion of the maritime fleet, social benefits can be realized, counteracting the social costs associated with MDO.

Government incentives are crucial for expediting the transition to greener energy and fuels, given that fossil fuels significantly contribute to global warming. These incentives include tax allowances, carbon allowances, equipment subsidies, land allocations, low-interest rate investment loans, high-price purchasing guarantees, customs duty exemptions, and incentives for green hydrogen production, particularly for maritime applications.

Sustainability

Sustainability plays a pivotal role in the context of the various discussions in the text. Whether assessing the emissions of different propulsion systems in the maritime sector, evaluating energy efficiency, or considering the environmental impact of alternative fuels such as green hydrogen and solid oxide fuel cells, the sustainability factor is ever present. It becomes evident that while emerging technologies may offer environmental benefits, they often come with higher emissions during the manufacturing phase or increased maintenance requirements, raising questions about their long-term sustainability. Furthermore, the financial implications of adopting cleaner technologies and their associated costs versus benefits are central to the sustainability discourse, highlighting the need for government incentives to transition to greener energy sources. Sustainability is not merely an ecological concept but a multifaceted consideration that encompasses economic, environmental, and societal aspects, ultimately guiding decisions in striving for a more sustainable future in the maritime and energy sectors.

Conclusion

This chapter has represented findings on offshore wind power for the production of green hydrogen, Life cycle assessment, and life cycle cost assessment of MDO, GH_2 ICE, and GH_2 SOFC. The study used Microsoft Excel to analyze the data collected on the three propulsion systems.

Chapter 5: Case Study

In 2021, South Africa joined the H2 Initiative, a platform fostering cooperation among international governments and industries. Projections indicate that by 2030, the countries involved in this initiative will collectively produce around 2 billion liters of green hydrogen, potentially challenging the oil industry's dominance (IEA, 2022a). In 2022, South African mining company Anglo-America introduced its prototype H_2-fueled mine haul truck. The nation's abundance of minerals, such as platinum and iridium, positions it to contribute to the local production of electrolyzers and fuel cells (Anglo-America, 2020). This initiative holds the potential to address South Africa's socio-economic challenges and energy crises while accelerating the transition away from fossil fuels, particularly coal, on which the country heavily relies for electricity.

The maritime industry stands to benefit significantly from South Africa's hydrogen production, especially since South Africa has aligned itself with the European Green Corridor. This collaboration could assist the region in producing and exporting hydrogen to Europe, meet domestic consumption needs, and support hydrogen-powered bunkering vessels. South Africa, Mexico, and India have joined forces in the maritime sector with the P4G Getting to Zero Coalition Partnership, which aims to develop zero-emission fuels and vessels (P4G, 2022).

Its natural resource abundance buoys South Africa's plans for producing green hydrogen (GH2) from renewable sources. With estimated daily solar radiation of 5 - 7 kWh/m^2 and approximately 80.54 TWh of wind power at wind speeds of 5-10 m/s across the country, the potential for renewable energy generation is substantial. Notably, in locations such as Saldanha Bay (Western Cape) and Boegoebaai (Northern Cape), the government is considering collaborating with local company SASOL to produce green liquid hydrogen (LH_2), ammonia, and methanol for maritime propulsion and fuel.

Chapter 6: Conclusion and Recommendations

Conclusion

In conclusion, Saldanha Bay's abundant wind resource positions the country to engage in carbon-free hydrogen production for both export and domestic markets. Wind energy development is progressively overtaking coal as a more cost-effective alternative, thus making hydrogen production an attractive option.

However, the current cost of hydrogen production, mainly through wind energy and Solid Oxide Fuel Cell (SOFC) electrolyzers, is relatively high, even though SOFC technology is still in its early stages. It's important to note that these costs are subject to change and may decrease as the technology matures and advances.

A significant advantage of Saldanha Bay is its focus on utilizing desalination for hydrogen production, which minimizes stress on freshwater resources, addressing water scarcity concerns. Nevertheless, it's essential to consider that, even with the potential for cost reductions in the future, the current cost of producing hydrogen using wind energy and SOFC technology is higher when compared to methods such as Steam Methane Reforming (SMR) through coal, especially if carbon taxes are taken into account. Despite the challenges, the shift towards renewable energy sources, such as wind, promises more sustainable and environmentally friendly hydrogen production.

The study considered the life cycle of a 2-stroke chemical tanker and performed an environmental impact assessment of three propulsion systems: MDO, GH_2 ICE, and SOFC. The research also explored the carbon credit costs and their incorporation into the MDO system, as opposed to the other systems, or their utilization as cost reduction or savings for cleaner fuel. The investigation covered the LCA and LCCA of a vessel's propulsion system over a 30-year lifespan. The key findings are as follows:

- MDO (0.5 $kgCO_2$ eq./kWh) has more emissions than the other propulsion systems, mainly emitted during the TTW phase. GH2 emissions, on the other hand, are concentrated during the WTT phase.
- The institutions (IMO and IPCC) each have their scope for LCA. IMO is narrower focused than IPCC, hence the 3-emission factor for LCA. The IPCC, on the other hand, emphasizes black carbon to indicate its significant emissions,

which is a minor variation between the two frameworks when comparing IMO and IPCC guidelines.

- Engine material indicated that fuel cells emit more during manufacturing due to the required electricity. In the operation phase, fuel stacks must be frequently replaced annually and replaced every six years. Fuel cells, however, are more efficient than ICE fueled by GH_2.
- The NPV analysis reveals that MDO is a feasible option compared to the other two propulsion systems. Even when considering carbon credit, MDO remains a viable choice. However, it should be noted that GH_2 may face challenges in attracting investors due to its negative NPV, and a social benefit was identified as a suitable incentive for investment purposes
- Given South Africa’s abundant wind energy resources, especially offshore, there is a call for further exploration of GH_2. The generation revenue analysis indicates a positive NPV, suggesting that it represents a sound investment opportunity.
- In conclusion, the SWOT analysis of hydrogen production and life cycle cost assessment in South Africa reveals significant strengths in abundant renewable energy resources, such as wind, which can be harnessed for green hydrogen production. However, it also highlights weaknesses related to the current high production costs and technological immaturity, emphasizing the potential for cost reductions in the future. Opportunities lie in accelerating decarbonization through social benefit projects and improving the energy economy ratio for hydrogen, while threats include competition from cheaper, conventional hydrogen production methods. Overall, South Africa's strategic focus on leveraging its renewable energy assets and addressing cost challenges can pave the way for sustainable and economically viable hydrogen production and use in the country.

Recommendations

- Social Benefit: Encouraging the maritime industry to engage in social benefit projects directly contributing to GHG emission reduction is commendable. These projects can include initiatives such as emissions offset programs, carbon capture and storage, and promoting sustainable and environmentally friendly technologies. By actively participating in such projects, the industry can play a pivotal role in accelerating GHG emissions reduction and achieving decarbonization goals.

- Mandatory Use of Life Cycle Assessment (LCA): Ensuring LCA and supply chain analysis mandatory within the maritime industry is a sound approach. This will ensure that all aspects of a product's life cycle, from raw material extraction to end-of-life disposal, are considered. This holistic perspective is crucial for making informed decisions about environmental impacts and emissions reduction. Assigning such assessments will help drive sustainable practices and transparency throughout the industry.
- Energy Economy Ratio: Considering an energy economy ratio, particularly about the energy density of hydrogen, is a noteworthy recommendation. Lowering the cost of fuel cells and green hydrogen is critical to promoting their adoption in the maritime sector. Improving the energy economy ratio and making hydrogen more cost-effective will become a more attractive alternative to conventional fuels, further accelerating the industry's decarbonization efforts.
- Transdisciplinary Research and Development: Emphasizing the importance of transdisciplinary research and development in energy conversion technology is critical. Collaborative efforts across various fields of science and engineering are essential for innovating and developing new technologies that can lead maritime transportation to net-zero emissions before 2040. This approach fosters innovation and the integration of emerging technologies into the industry.

These recommendations collectively provide a comprehensive and proactive approach to tackling the challenges of GHG emissions in the maritime sector, ultimately contributing to a more sustainable and environmentally responsible international maritime industry.

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Appendices

Table 18 Provides the gravimetric and volumetric for fuel types. Adopted from Wang et al., (2019)

Fuel Type	**Gravimetric (kWh/kg)**	**Volumetric (kWh/L)**
Compressed GH2	33.33	1.39
Liquid GH2	33.33	2.36
MDO	11.39	10.42

Table 19 shows the cost of hydrogen using the energy economy ratio (g/kWh)

Energy Density			
	3,663003663	g/kWh	
	7657483,352	g/kWh	Energy Required the 1st year
	376 706 830,5	g/kWh	
	376 706,8	kg/kWh	
$	4 708 835,38		1st year
$	**141 265 061,44**		**30 years**
$	730 943,88		Difference with MDO
$	**727 790,88**		**Positive Value (without Carbon Credit)**