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Sustainable Fuel Supply for Very Small Island Transportation: The Potential of Hybrid Renewable Energy and Green Hydrogen

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Abstract: The transition to a low-carbon future necessitates innovative approaches to renewable energy deployment, particularly in the marine environment, where abundant resources remain underutilized. This paper explores the potential of hybrid renewable energy systems and green hydrogen production to address the energy challenges faced by Very Small Islands (VSIs). These islands heavily rely on imported fossil fuels, making them vulnerable to global price fluctuations and contributing to economic instability and environmental degradation. Offshore floating platforms present a transformative opportunity by harnessing marine renewable resources, integrating wind, solar, and wave energy to maximize energy production while minimizing land use conflicts. Green hydrogen, produced through electrolysis of sea water, powered by these renewable sources, offers a sustainable alternative for decarbonizing transportation, particularly in the maritime sector. The study aims to assess the feasibility of converting small conventional passenger vessel to hydrogen propulsion and evaluate the technical, economic, and environmental impacts of deploying offshore platform for hydrogen production. By examining these aspects, this research contributes to the broader discourse on sustainable energy solutions for island communities and provides actionable insights into implementing renewable hydrogen-based maritime transport.

Keywords: Fuel supply; very small island transportation; hybrid renewable energy; offshore platforms; green hydrogen; seawater electrolysis

1. Introduction

The transition to a low-carbon future necessitates innovative approaches to renewable energy deployment, particularly in the marine environment, where abundant resources remain underutilized. Green alternative energy sources represent solution in that energy transition. As technological advancements continue and supportive policies are implemented, green hydrogen is poised to play a critical role in shaping a cleaner, more resilient future [1].

Very Small Islands (VSIs) face distinct energy challenges that hinder their socio-economic development and environmental sustainability [2]. Each country has its own definition of a "small island" according to geographical and administrative criterions, local culture and traditions, etc. [3]. In Greece, small islands are defined as having a population of less than 4,000 inhabitants [3]. The heavy reliance on imported fossil fuels makes these regions highly susceptible to global fuel price fluctuations, creating economic instability and increasing the cost of essential services, including transportation [4]. Maritime transport between small islands and the mainland or administrative center, is a major energy consumer, often reliant on diesel-powered vessels [5]. In many cases, fuel imports account for a substantial portion of the gross domestic product in these regions, creating vulnerabilities that hinder socio-economic development [6].

A key limitation faced by VSIs is the scarcity of available land for large-scale renewable energy installations. The competing demands for residential, commercial, and agricultural land restrict the deployment of land-based renewable energy systems. In response, offshore floating platforms present a transformative opportunity by harnessing the vast renewable energy resources available in the marine environment [7,8]. These platforms can integrate multiple renewable energy sources, including offshore wind, solar, and wave energy, thereby maximizing energy production while minimizing land use conflicts and environmental impact [9,10,11].

Offshore wind power has emerged as a significant contributor to renewable energy generation globally [11]. Solar Energy systems offer a promising avenue for complementing wind power, particularly in regions with high solar irradiance [10]. Additionally wave energy presents a significant untapped potential for renewable energy generation in coastal regions [12]. By integrating these diverse sources, hybrid systems can achieve a more consistent and reliable power output, minimizing the impact of intermittency and maximizing energy production throughout the year [10].

Green hydrogen, produced through the electrolysis of water using renewable energy sources, offers a promising pathway towards decarbonizing various sectors, including transportation [13,14]. Seawater, a readily available and abundant resource, presents a compelling feedstock for hydrogen production, particularly in coastal regions [15,16]. The integration of offshore renewable energy sources, such as wind, solar, and wave energy, with seawater electrolysis offers a synergistic approach to green hydrogen production [9]. Its ability to store and transport energy efficiently makes it a viable solution for overcoming the intermittent nature of renewable energy sources. By leveraging offshore-generated renewable energy, green hydrogen can be produced and stored on floating platforms, providing a stable and clean energy supply for island communities and their essential services.

A critical application of green hydrogen in VSIs may be the decarbonization of sea transport. Many small islands rely on frequent and flexible passenger ferry services to maintain economic and administrative connections with larger neighboring islands or mainland regions. These vessels currently operate on fossil fuels, contributing significantly to carbon emissions and air pollution. Converting a conventional small passenger vessel to operate on green hydrogen can demonstrate the feasibility and benefits of this technology. The success of this transition can serve as a model for other small island ferry services worldwide.

Most of the existing research focuses on economies of scale hydrogen production offshore platforms, or larger vessels and long-distance shipping, but small island transportation has unique challenges and requirements. This study addresses this gap by concentrating on a small, flexible passenger vessel that serves a small island. The paper aims to contribute to the renewable energy field by offering insights into the role of marine renewable energy in facilitating the global transition to a low-carbon future particularly in very small island transportation.

A systematic literature review will be conducted to gather existing knowledge on offshore renewable energy technologies, green hydrogen production, and sustainable transportation solutions for Very Small Islands (VSIs). This review will focus on recent studies (published within the last five years) that address the challenges and opportunities associated with renewable energy deployment in marine environments. Key topics will include:

The potential of hybrid renewable energy systems integrating wind, solar, and wave energy, the current state of green hydrogen production technologies and their applicability in offshore settings, and case studies of successful hydrogen-powered maritime transportation initiatives.

Then a case is analyzed to shed light to the feasibility of deploying offshore floating platforms for green hydrogen production and utilizing this hydrogen to convert a small, flexible passenger vessel from conventional, fossil fuels to green hydrogen propulsion. By examining benefits and challenges, this research will contribute to the broader discourse on sustainable energy solutions for island communities and provide actionable insights into implementing renewable hydrogen-based maritime transport.

The rest of the paper is structured as follows: Section 2 provides a comprehensive literature review, covering the energy challenges faced by small islands, the potential of hybrid renewable energy systems, existing research on green hydrogen and seawater electrolysis, hydrogen-powered maritime transportation, challenges in offshore hydrogen production, and lessons learned from existing hydrogen-based propulsion projects. Section 3 presents a hypothetical case study, including the description of a floating platform for hydrogen production, the estimated hydrogen fuel requirements for a local ferry, and the energy needed to produce compressed hydrogen fuel by electrolysis. Section 4 discusses the integration of hydrogen fuel into the production-consumption system, focusing on hydrogen production on offshore platform and its application in vessel propulsion. Section 5 offers a discussion of the findings, and Section 6 concludes the paper by summarizing the key insights and their implications for sustainable fuel supply in very small island transportation.

2. Literature Review

2.1. Energy Challenges in Small Islands

Geographic isolation, limited natural resources, and a heavy reliance on imported fossil fuels present significant energy challenges for VSIs. The dependence on imported energy sources leaves these regions susceptible to global fuel price volatility, resulting in increased energy costs for essential services, such as transportation, and ultimately contributing to economic instability. Electricity generation on islands is often up to ten times more expensive than on mainland territories, primarily due to the widespread use of diesel generators and the logistical complexities of fuel transportation [17].

The continued use of diesel-powered vessels for maritime transport in small islands poses significant environmental and economic challenges, hindering their transition towards a more sustainable future. The high costs associated with fuel imports directly affect the affordability and reliability of these services, further straining local economies. As island populations grow and economies develop, the demand for transportation energy is expected to rise, exacerbating existing fuel security issues. This combination of increasing energy demand and dependence on imported fossil fuels creates a precarious situation for VSIs, underscoring the urgent need for sustainable energy solutions [18].

In response to these challenges, there is a growing recognition of the need for innovative strategies that leverage local renewable energy resources. Studies suggest that integrating decentralized renewable energy systems—such as solar, wind, and biomass—can enhance energy security while reducing reliance on fossil fuels [19]. By developing localized energy solutions that utilize available resources, VSIs can improve their resilience against external shocks and create more sustainable transportation systems that contribute to broader decarbonization goals [20].

2.2. Renewable energy generation from hybrid systems

The integration of multiple renewable energy sources, such as wind, solar, and wave energy, into a single hybrid system offers a promising approach to enhance renewable energy generation and grid stability [9,10,11]. This multifaceted strategy leverages the strengths of each energy source, mitigating the intermittency associated with individual sources and improving overall system reliability and efficiency [9,10]. A key limitation faced by VSIs is the scarcity of available land for large-scale renewable energy installations. The competing demands for residential, commercial, and agricultural land restrict the deployment of land-based renewable energy systems.

In response, offshore floating platforms present a transformative opportunity by harnessing the vast renewable energy resources available in the marine environment. These platforms can integrate multiple renewable energy sources, including offshore wind, solar, and wave energy, thereby maximizing energy production while minimizing land use conflicts and environmental impact. Offshore wind power has emerged as a significant contributor to renewable energy generation globally [11]. Solar Energy systems offer a promising avenue for complementing wind power, particularly in regions with high solar irradiance [10]. Additionally wave energy presents a significant untapped potential for renewable energy generation in coastal regions [12].

By integrating these diverse sources, hybrid systems can achieve a more consistent and reliable power output, minimizing the impact of intermittency and maximizing energy production throughout the year [10]. The integration of solar, wave, and wind energy into a single hybrid system represents a transformative approach to renewable energy generation. This multifaceted strategy leverages the strengths of each energy source, enhancing overall efficiency, stability, and sustainability. This approach has garnered significant research attention, with studies exploring various hybrid configurations and their potential benefits [11]. For example, hybrid wind-wave energy systems have been extensively investigated, with a focus on optimizing power conversion techniques, response coupling, and control schemes [9].

While significant progress has been made, challenges remain in optimizing the integration of these diverse sources and ensuring the efficient and reliable operation of hybrid systems. Further research and development are crucial to address these challenges and unlock the full potential of hybrid renewable energy systems for a sustainable energy future. One of the primary benefits of integrating solar, wind, and wave energy is the complementary nature of these resources. Solar energy production peaks during sunny days, while wind energy often generates more power at night or during stormy weather. Wave energy, on the other hand, can provide a consistent output due to its predictability in coastal areas. By combining these sources, hybrid systems can deliver a more stable and reliable energy supply, reducing the intermittency issues associated with solar and wind alone [12]. A recent study conducted in the Aegean Sea evaluated a hybrid renewable energy system combining offshore wind, solar PV, and wave energy for a small island community [21]. The system included a 60 kW offshore wind turbine, a 40 kW solar PV array, and a 20 kW wave energy converter. The hybrid system reduced daily energy variability by 55% compared to standalone systems, and the grid instability incidents by 45%, as the combined output smoothed out fluctuations in renewable energy generation. The results demonstrated significant improvements in energy output stability and reliability, highlighting the synergies of integrating multiple renewable energy sources.

This synergy allows for better resource utilization and enhances the overall efficiency of energy production.

2.3. Green Hydrogen and Seawater Electrolysis.

Green hydrogen, produced through the electrolysis of water using renewable energy sources, offers a promising pathway towards decarbonizing various sectors, including transportation [13,14,22]. Seawater, a readily available and abundant resource, presents a compelling feedstock for hydrogen production, particularly in coastal regions [15,16]. The integration of offshore renewable energy sources, such as wind, solar, and wave energy, with seawater electrolysis offers a synergistic approach to green hydrogen production [9]. Offshore platforms can provide a stable and reliable platform for hosting renewable energy generation systems, while simultaneously providing access to abundant seawater for electrolysis. This co-location can optimize energy utilization, minimize transmission losses, and enhance the overall efficiency of the system.

The design and deployment of offshore platforms for renewable energy generation require careful consideration of various factors, including environmental impacts, structural integrity, and maintenance requirements. Minimizing the environmental impact on marine ecosystems is crucial. Careful site selection, environmental impact assessments, and mitigation measures are necessary to protect marine life and habitats. Platforms must be designed to withstand harsh marine environments, including strong winds, waves, and currents. Regular maintenance and inspection of offshore platforms are essential to ensure their long-term operation and safety.

While seawater electrolysis offers significant potential, several challenges need to be addressed to ensure its technical and economic feasibility. The corrosive nature of seawater can significantly impact the durability and performance of electrolyzer components [23,15]. The presence of salts and other impurities in seawater can lead to membrane fouling, reducing efficiency and increasing maintenance requirements [24]. Developing efficient and durable electrocatalysts that can withstand the harsh conditions of seawater electrolysis is crucial [23,16]. Maximizing the efficiency of the entire process, from renewable energy generation to hydrogen production and compression, is critical to ensure the economic viability of seawater electrolysis.

Despite these challenges, ongoing research and development efforts are focused on addressing these issues and improving the efficiency and cost-effectiveness of seawater electrolysis.

2.4. Hydrogen-Powered Maritime Transportation

The maritime industry faces increasing pressure to decarbonize, driven by international regulations like the IMO's MARPOL Annex VI, which mandates energy efficiency and emission reduction measures [25]. Hydrogen emerges as a promising alternative fuel due to its potential for zero-carbon emissions when produced from renewable sources [26,27,28]. It can be utilized in fuel cells or combustion engines to power marine vessels [27,29].

Fuel cells offer high efficiency, minimal vibration and noise, zero emissions [30,29]. Proton Exchange Membrane Fuel Cells (PEMFCs) are considered particularly suitable for maritime applications [26]. Hybrid systems combining fuel cells with batteries enhance flexibility and efficiency [26]. On the other hand, hydrogen in combustion Engines offers compatibility with existing ship structures and lower purity hydrogen requirements [29]. Limitations are lower efficiency, potential for emissions (though NOx emissions can be reduced through strategies like unburned hydrogen), and slower transient response [29].

High-pressure gaseous hydrogen storage offers limited storage density, suitable primarily for short-range vessels [29]. Liquid hydrogen (LH_2) offers higher energy density but requires specialized technologies [29,26]. Other promising storage options include liquid organic hydrogen carriers (LOHCs), methanol reforming, metal hydrolysis, and alloy hydrogen storage [29].

Early adopters and case studies demonstrate the feasibility of hydrogen-powered vessels. The "Viking Lady" was the world's first ship to operate with a fuel cell propulsion system [30], while the "H2R-Evolution" superyacht showcases a combination of hydrogen fuel cells, lithium batteries, and solar panels [30]. Other notable examples include the "J Zero" passenger ferry in Norway and the "Hydrotug 1" in the Port of Antwerp-Bruges, both powered by fuel cells. The Japanese "Hydro Bingo" ferry exemplifies the use of hydrogen combustion engines alongside diesel engines [30].

Beyond fuel cells and combustion engines, emerging trends include the Stena Germanica, a RoPax ferry converted to operate on hydrogen [31], and the Commissioning Service Operation Vessel (CSOV) Edda Breeze and the Windcat Workboats series, which utilize hydrogen propulsion systems [31]. The "Energy Observer" demonstrates the integration of renewable energy generation (wind, solar) with on-board hydrogen production [30]. Projects like DNV's Thames Hydrogen Eco-project and Samsung Heavy Industries' collaboration with Bloom Energy are exploring the integration of hydrogen technologies in various maritime applications [29].

These case studies demonstrate the feasibility of hydrogen-powered vessels and point towards a future where hydrogen plays a significant role in decarbonizing maritime transport. However, further development is needed to address the challenges related to hydrogen storage, safety, and economic viability.

2.5. Challenges in Offshore Hydrogen Production

Offshore hydrogen production presents unique challenges that span technical, economic, and regulatory domains. Addressing these is crucial for the successful implementation of hydrogen as a sustainable fuel for the maritime industry.

2.5.1. Technical Challenges:

Two options exist for electrolysis of seawater, one involves complete desalination and removal of dissolved salts, which requires more energy. The other involves directly using seawater, which might damage the system. The best method for producing hydrogen from seawater has not been determined yet and is being studied [27].

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The marine environment is inherently corrosive due to the presence of salt in both the air and water. This poses a significant challenge to the durability of fuel cells, electrolyzers, and other equipment [26]. The presence of salt can lead to accelerated corrosion and degradation of materials, necessitating the use of specialized, corrosion-resistant components, which may increase costs [26,28,29]. In offshore operations, the purity of water used for electrolysis is a concern. Seawater needs to be desalinated and purified before being used in electrolyzers. Contaminants in the water, even after desalination, can impact the performance and lifetime of fuel cells [27,30]. Additionally, the presence of salt in the air can also lead to contamination issues [26].

Offshore hydrogen production systems must be designed for high reliability in harsh conditions, withstanding vibrations, variable weather conditions, and potential impacts [26,28,29]. Maintaining consistent hydrogen production and avoiding downtime is essential for a reliable fuel supply [28,29]. There are concerns about the durability of fuel cells in the marine environment and long-term tests are needed to determine how well they hold up under real-world conditions [26]. Because hydrogen is highly flammable and has a low density, it is prone to leakage, making detection challenging. This presents safety risks, especially in enclosed spaces on ships [29] ; [30].

Materials used in offshore hydrogen systems are susceptible to hydrogen embrittlement, especially in high-pressure environments. This can compromise structural integrity and lead to failures [29] ; [30]. Offshore hydrogen production is often coupled with renewable energy sources like wind and wave power [28,30]. Integrating these intermittent sources with the hydrogen production process presents challenges in terms of power management, storage, and ensuring a stable hydrogen supply [31].

2.5.2. Economic Challenges:

Setting up offshore hydrogen production facilities involves high initial capital expenditures (CAPEX). Wave energy converters and electrolyzers account for the largest costs [28]. Costs of hydrogen production and storage technologies, especially if derived from renewable sources, are not yet competitive with conventional fuels [26,30]. The current market for green hydrogen is still developing. The price of green hydrogen must be lower to compete with conventional oil-based fuels. The lack of an established hydrogen supply chain and bunkering infrastructure contributes to the high cost of hydrogen fuel [26,30]. There are no specialized demonstration projects for hydrogen refuelling in maritime contexts [30].

2.5.3. Regulatory Challenges:

The regulatory landscape for offshore hydrogen projects is complex and involves obtaining approvals and permits. Unlike conventional fuels, which have established supply chains, hydrogen requires a new regulatory framework that is still under development, with specific protocols for its use on ships [26,30]. There is a lack of comprehensive safety standards for hydrogen-powered ships, which also applies to hydrogen production, storage, and transportation. Existing standards are primarily based on automotive applications and need to be adapted to the maritime sector [29,30]. Differences in international standards could lead to a lack of technology and market coordination and will require cooperation to align safety standards.

Addressing these multifaceted challenges will require technological innovation, policy support, and industry collaboration. The development of cost-effective and durable offshore hydrogen production technologies, along with the establishment of robust regulatory frameworks, is essential for realizing the full potential of hydrogen as a sustainable maritime fuel.

2.6. Lessons learned from existing projects on hydrogen-based propulsion systems

Existing projects demonstrate the feasibility of hydrogen propulsion in the maritime sector, albeit primarily in the experimental phase and largely limited to smaller vessels serving as platforms for evaluating various technological solutions [31]. The "Viking Lady" project provides valuable real-world data from the operation of a Molten Carbonate Fuel Cell (MCFC) for over 18,500 hours [31]. The "Energy Observer" exemplifies a comprehensive approach, integrating renewable energy generation (wind, solar) with hydrogen production and propulsion [30].

Fuel cell technologies, particularly Proton Exchange Membrane Fuel Cells (PEMFCs), have shown promise due to their high-power density and low-temperature operation [26]. However, their current power output may be insufficient for larger ocean-going vessels [29]. Higher-temperature fuel cells, such as solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs), offer higher power output and potential for combined heat and power generation, making them more suitable for larger vessels [29]. Hybrid systems combining fuel cells with batteries have demonstrated improved efficiency and flexibility in applications such as small RoRo vessels and passenger ferries [26,27,31].

Hydrogen storage remains a significant challenge. High-pressure gaseous hydrogen storage offers limited storage density, suitable primarily for short-range vessels [29]. Liquid hydrogen (LH_2) storage offers higher energy density but requires specialized technologies [29,26]. Other promising storage options include liquid organic hydrogen carriers (LOHCs), methanol reforming, metal hydrolysis, and alloy hydrogen storage [29]. Safe and reliable deployment of hydrogen storage systems is crucial, requiring further research and development to address challenges such as hydrogen embrittlement [29].

The development of international and regional policy frameworks and incentive mechanisms to regulate the use of alternative power systems in marine environments is crucial [30]. High construction and operational costs, including the levelized cost of hydrogen (LCOH), remain a significant barrier to widespread adoption of fuel cell systems [28,30].

Ongoing research and development are crucial to address the technical, economic, and safety challenges associated with hydrogen propulsion in the maritime sector. This includes further development of efficient and durable fuel cell technologies, advancements in hydrogen storage and distribution, and the integration of renewable energy sources, such as offshore wind and solar, with seawater electrolysis for sustainable hydrogen production [27,29].

2.7. Rationale for the Study

The review of the literature creates the motivation to deepen the study of the dependence of a very small island’s marine transportation on conventional, fossil fuels. In this direction, the decentralized production of green alternative fuel (e.g. hydrogen) can be studied, on a platform near the coast, which will combine more than one renewable energy form. The produced fuel will be used to cover the needs of a small local boat after the required retrofitting, contributing to its de-independence from fossil fuels.

A case study examining the use of green hydrogen, produced on an offshore floating platform, for the propulsion of a small passenger vessel is valuable because it addresses key issues and gaps in current research and the practical application of hydrogen in the maritime sector, particularly for smaller-scale operations.

Much of the existing research focuses on larger vessels and long-distance shipping, but small island transportation has unique challenges and requirements. This study addresses this gap by concentrating on a small, flexible passenger vessel. This is particularly important for island communities, which rely heavily on maritime transport for connectivity and tourism. The use of an offshore floating platform for green hydrogen production is a relatively novel approach, combining renewable energy generation with hydrogen production. This method can overcome the limitations of land-based infrastructure and make hydrogen more accessible in remote locations. The study will contribute valuable insights into the technical, economic, and practical aspects of transitioning to a sustainable maritime sector, especially for small island communities. This type of research is necessary to move beyond theoretical studies towards more tangible solutions that can contribute to the decarbonization goals of the maritime industry.

3. Case Study

3.1. Presentation of a hypothetical case study on floating platform

Sea transport to the nearest coast that serves the small islands administratively and economically is carried out by small and flexible ships with daily frequency (for example, the connection between a small Greek island of Oinousses and the island Chios), operating on fossil fuels. These fossil fuels are imported and transported to the island via a lengthy journey, contributing to significant environmental concerns such as greenhouse gas emissions and air pollution, while also imposing economic burdens due to high transportation costs and reliance on volatile global fuel markets. Politically, this dependence on imported fossil fuels undermines energy security and hinders the transition to sustainable energy solutions, complicating efforts to achieve decarbonization goals.

The hypothetical case study consists of calculating the energy to produce green hydrogen necessary for a small passenger vessel that connects the small island of Oinousses with the nearby island of Chios. In this part of the paper the characteristics of the area of study and the technical and operational characteristics of the ship are presented.

The islands of Chios and Oinousses are located at the Northeastern Aegean Sea (Figure 1). Chios has a population of 51,962 inhabitants and Oinousses a population of 911 inhabitants in 2021 [32]. The economic, societal, and environmental conditions of Chios and Oinousses are typical of the insular areas of the Eastern Mediterranean. A unique characteristic is that a very important source of income is ocean shipping with nearly half of the Greek shipowners that are now active all over the globe having their origin either from Chios or from Oinousses. The Greek owned ships comprise 17% of the global tonnage (as DWT) [33]. As a result, a proportion of the workforce of the islands is employed in ocean going ships of Chian and Oinoussian interests. Other economic activities include agriculture, livestock farming, public services and tourism.

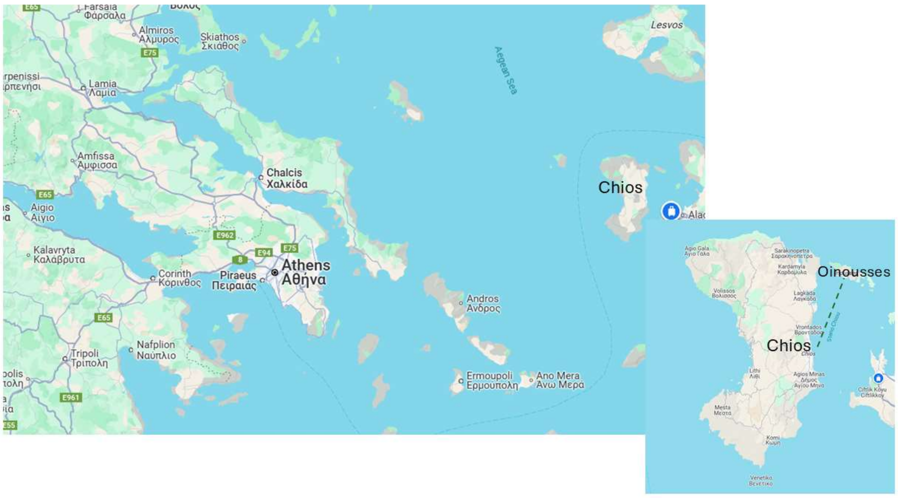

Figure 1. Map of Chios and Oinousses and the itinerary that connects the two islands (Source: GoogleMaps).

For the connection of Oinousses with Chios, a small Ro-Ro/Passenger ship is used (Table 1). The ship connects daily the islands. There is an itinerary in the morning (8:00 AM LT) from Oinousses to Chios and another one in the afternoon (2:00 PM LT) from Chios back to Oinousses. The duration of the trip is 45 minutes.

Table 1. The characteristics of the ship under study.

Characteristic	Value
Ship type	Ro-Ro passenger
Manager/owner	Oinoussian Friends Association
Flag	Greece
Gross tonnage	365
Summer deadweight (t)	80
Length overall (m)	42.77
Beam (m)	8.4
Year of built	1997
Main engine power (hp)	2x500
Auxiliary engine power (hp)	2X120
Fuel type	Marine Diesel Oil
Fuel consumption (L/h)	200
Service speed (knots)	10.6
Maneuvering time (entry into port) (min)	5
Maneuvering time (departing from the port) (min)	3
Navigation time (min)	45
Hotelling (at berth) time (h)	22.2

Sources: Marine Traffic, Personal communication with ship's engineer.

A hypothetical case could study the supply of hydrogen fuel for the transportation needs of the island, produced on a platform, installed offshore, but near the coast. This study builds on the results of recent papers for the same island that presented renewable energy production used to desalinate water, and support aquaculture [34,8,35]. The offshore platform intended to provide 1,000 m^3 of fresh water per day by desalinating sea water utilizing combined wind, solar, and wave energy sources, estimated annual energy production within the range of 1,444 MWh and 1,627 MWh, based on Homer software modelling [36].

Currently, in the MUSICA project a floating offshore platform is being designed and constructed, that will have a 500kW wind turbine and photovoltaic panels with a total of 60kW [37];[38]. This platform will be installed near the shore of Oinousses. It is estimated that the total energy produced in a year by the platform will be between 1807 -1965 MWh/year.

The MUSICA platform is a multipurpose platform. There is a desalination system, a wave energy system and an aquaculture. The desalination system consists of two reverse osmosis (RO) units with the capacity to produce 5 lit/h and 10 lit/h of potable water from the sea water. In total the system will have the capacity to produce 360 tons/day of potable water, that requires 2.1-2.8 MWh per day. The wind turbine is estimated to produce between 1725 – 1879 MWh/year and the photovoltaic system is estimated to produce between 82 – 86 MWh/year.

Two meteorological stations have been installed in the city of Chios and in Kardamyla, Chios, respectively, that are used to record the meteorological data for the MUSICA Project [39]. These data are used to better predict the energy that will be produced by the renewable energy systems.

3.2. Estimated hydrogen fuel in the case study

A small passenger vessel connecting Oinousses and Chios, two neighboring Greek islands in Aegean Sea, operating at moderate speeds (around 10.6 knots) might consume approximately 200 liters per hour, or 2,000 lit/week (according to the managing office) Marine Diesel Oil (MDO).

The determination of the hydrogen fuel equivalent of 2 cubic meters (2,000 liters) of Marine Diesel Oil (MDO) could be based on the energy content and density of both fuels.

Using the energy content of the conventional Marine Diesel Oil (MDO) and hydrogen, the required hydrogen can be estimated.

Table 2. Comparison of MDO and Hydrogen.

Parameter	Marine Diesel Oil (MDO)	Hydrogen (350 bar)	Hydrogen (700 bar)
Energy Content (LHV)	42.7 MJ/kg	120 MJ/kg	120 MJ/kg
Density	0.85 kg/L	0.024 kg/L	0.040 kg/L
Energy per Liter	36.3 MJ/L	2.88 MJ/L	4.8 MJ/L

The low density of hydrogen presents challenges for storage and transportation, necessitating high-pressure tanks or liquefaction to make hydrogen practical for use in applications such as maritime transport. The contrasting characteristics of MDO and hydrogen fuel highlight the need for innovative solutions to harness hydrogen's potential while addressing the challenges associated with its low density.

Compressed hydrogen gas exhibits significantly different storage characteristics compared to traditional fuel Marine Diesel Oil (MDO). At a pressure of 350 bar, the volumetric density of hydrogen is approximately 25 kg/m^3 [40]. This increased density allows for a more efficient storage solution compared to hydrogen at atmospheric pressure, which has a density of about 0.089 kg/m^3 [41]. When the pressure is raised to 700 bar, the volumetric density of hydrogen increases further to about 42 kg/m^3 [42]. These high-pressure storage capabilities are crucial for applications such as fuel cell electric vehicles, where maximizing the amount of hydrogen stored in a limited space is essential for operational efficiency and range. The ability to compress hydrogen at these pressures enables its practical use as a clean fuel alternative, particularly in maritime transportation where space and weight constraints are significant considerations.

Using the energy content of the conventional Marine Diesel Oil (MDO) that is needed for the propulsion of the ship (2,000 Litters per week) and the energy content of hydrogen, the required hydrogen volume for the specific case can be estimated (Table 2).

Table 3. Hydrogen Equivalent to Marine Diesel Oil (2 m^3).

Energy Content (MJ)	Hydrogen Mass (kg)	Hydrogen Volume at 350 bar (m^3)	Hydrogen Volume at 700 bar (m^3)
72,600 MJ	≈ 605 kg	≈ 25.2 m^3	≈ 15.1 m^3

As the maritime industry seeks to transition towards more sustainable fuel options, understanding these properties is crucial for developing effective strategies for hydrogen integration in marine applications.

3.3. Required energy to produce compressed hydrogen

To produce 605 kg of compressed hydrogen fuel at 350 bar or 700 bar from seawater, the energy requirements must account for three key processes: seawater desalination, electrolysis, and compression. This hydrogen is equivalent to 2 m^3 of Marine Diesel Oil (MDO), providing 72,600 MJ of energy that can cover the energy needs of a small vessel connecting the neighbouring islands of Chios and Oinousses for a week.

Water electrolysis is an electrochemical process in which electricity is used to split water into two gases, hydrogen and oxygen. The overall reaction of water electrolysis is expressed as

$$H_2O \rightarrow 1/2O_2 + H_2 \quad (1)$$

From the stoichiometry of the reaction, 1 mole (or 18 grams) of water produce 1 mole (or 2 grams) of hydrogen. In the case that we need 605 Kg of hydrogen there is a requirement of 5.4 tons of water to be electrolysed.

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Below is a detailed breakdown of the energy required for each step (Table 4). For the desalination energy, it was estimated that Reverse osmosis (RO) of sea water consumes approximately 3–4 kWh per m^3 of desalinated water [43]. Assuming that the density of desalinated water is close to 1 g/cm^3, then the energy needed to produce 5.4 tons of desalinated water is 16.2-21.6KWh.

Electrolysis is the most energy-intensive step, accounting for ~95% of the total energy requirement. The high energy demand underscores the importance of using cost-effective and efficient renewable energy sources, such as offshore wind or solar, to power the electrolyzers. Proton Exchange Membrane (PEM) electrolyzers, which are commonly used for green hydrogen production, have an efficiency of 70–80%, requiring 50–55 kWh per kg of hydrogen [44]. As a result, the energy to produce 605 kg of hydrogen is about 30,250 – 33,275 kWh.

Taking that the energy required to produce a kg of compressed hydrogen is : ~2.5 kWh/kg for 350 bar or ~5 kWh/kg for 700 bar [45], compression energy (350 bar) to produce 605 kg: 605 kg×2.5 kWh/kg=1,513 kWh, and similarly, the compression energy (700 bar) is 3,025 kWh. The required compression energy (350 bar) in the total is 1,513 kWh/ 31,784 kWh, or ~4.8%. Similarly, the Compression Energy (700 bar) is ~9.1%. While compressing hydrogen to 700 bar requires more energy than 350 bar, it significantly reduces the storage volume, making it more practical for maritime applications. The choice of storage pressure depends on the trade-off between energy consumption and storage space.

Table 4. Required energy to produce compressed hydrogen (605 Kg).

Process	Energy Required (kWh)
Seawater Desalination	16.2 – 21.6
Electrolysis	30,250 – 33,275
Compression (350 bar)	1,513
Compression (700 bar)	3,025
Total (350 bar)	**31,784 kWh**
Total (700 bar)	**33,296 kWh**

Electrolysis accounts for most of the energy required (~95%), highlighting the need for efficient and cost-effective renewable energy systems to power the process. Compressing hydrogen to 700 bar requires approximately double the energy of compressing to 350 bar, but it reduces the storage volume by ~40%, making it more suitable for space-constrained applications like maritime transport. The energy required for desalination is negligible compared to electrolysis and compression, but it is a critical step to ensure the quality of water for electrolysis.

4. Integration of hydrogen fuel in the production-consumption system

4.1. Hydrogen production integrated on a platform

For hydrogen production to be integrated into the platform utilizing wind, solar, and wave energy sources for a combined capacity, based on general knowledge of hydrogen production technologies, the following additions or modifications would likely be required:

Electrolyzer Integration: An electrolyzer is the core component for hydrogen production, using electricity to split water molecules into hydrogen and oxygen. The platform would need to incorporate an electrolyzer system of appropriate capacity to meet the desired hydrogen production levels. Different types of electrolyzers exist, including alkaline, PEM (proton exchange membrane), and solid oxide electrolyzers, each with its own advantages and disadvantages in terms of efficiency, cost, and operating conditions. The selection of the electrolyzer technology would depend on factors such as the available renewable energy supply, the desired hydrogen purity, and the overall system costs.

Power Management System Modifications: The platform's existing power management system, including the EMS, would need to be modified to accommodate the electrolyzer. This would involve, allocating sufficient power from the renewable energy sources to the electrolyzer. This may require increasing the capacity of the renewable energy generators or prioritizing hydrogen production during periods of high renewable energy availability.

Managing the variable power input from renewable sources: The electrolyzer's operation needs to be coordinated with the fluctuations in renewable energy generation to ensure efficient and stable hydrogen production. This may involve using the energy storage systems (CAES and batteries) to buffer the power supply to the electrolyzer.

Integrating the electrolyzer's control system with the platform's EMS: This integration would enable coordinated operation and optimization of the entire energy system, including hydrogen production.

Safety Systems: Hydrogen is flammable and requires careful handling. The platform would need to include safety systems such as gas detectors, ventilation systems, and fire suppression systems to mitigate potential risks.

Hydrogen Storage and Handling: Once produced, the hydrogen needs to be safely stored and handled. Depending on the desired storage capacity and the intended use of the hydrogen, appropriate storage tanks would need to be installed on the platform. These tanks could store hydrogen in gaseous form under high pressure or in liquid form at cryogenic temperatures. If high-pressure storage or liquid hydrogen storage is chosen, the platform would need to incorporate compression and/or liquefaction systems to convert the hydrogen to the desired state. Accommodating the electrolyzer, storage tanks, and other hydrogen-related equipment would require additional space on the platform. This might necessitate expanding the platform's size or reconfiguring the existing layout, by careful planning and engineering to ensure structural integrity and safe operation.

4.2. Integration of Hydrogen Fuel for Vessel Propulsion

Integrating hydrogen fuel for the propulsion of vessels involves several innovative technologies and methodologies that leverage hydrogen's potential as a clean energy source. Hydrogen fuel can be integrated into a vessel's propulsion system through two primary methods: hydrogen fuel cells and hydrogen combustion engines. The choice depends on vessel type, operational profile, and technical feasibility.

Fuel cells convert the chemical energy of hydrogen directly into electricity with high efficiency and low emissions [29,46,30]. They offer a cleaner alternative to traditional combustion engines by producing only water vapor and heat [47]. Proton Exchange Membrane Fuel Cells (PEMFCs) are a promising technology for marine applications due to their high power density, low operating temperature, and dynamic response [29,30]. PEMFCs can be used as the primary power source or as part of a hybrid system [26]. PEMFCs are suitable for dynamic operations due to their rapid start-up times [46]. Hybrid systems combine fuel cells with batteries, allowing the fuel cells to provide a steady base load while the batteries handle peak power demands [48]. This combination enhances system efficiency and reliability, and enables the use of smaller fuel cells [49,30]. Fuel cell systems can be scaled and arranged to meet the specific power requirements of different vessels [49]. The electricity generated by fuel cells is used to drive electric motors, which in turn propel the vessel [26]. Auxiliary power for lighting, ventilation, and other onboard systems can also be supplied by fuel cells or a combination of fuel cells and batteries [49].

5. Discussion

This study explored the feasibility of using green hydrogen produced from offshore hybrid renewable energy platforms to power small passenger vessels in VSIs. In the studied case the energy content a week fuel for a small vessel of Marine Diesel Oil (MDO), is equivalent to hydrogen, requiring 25.2 m^3 of storage at 350 bar or 15.1 m^3 at 700 bar. Producing that hydrogen requires 30,250–

33,275 kWh of energy, with electrolysis accounting for ~95% of the total energy requirement. Offshore hybrid renewable energy platforms, such as the one proposed near the coast of Oinousses Island, can generate 1,444–1,627 MWh annually, sufficient to support green hydrogen production. Energy production depends on weather conditions, and therefore energy storage is required to ensure smooth hydrogen production. On the other hand, seasonality in passenger traffic, with more routes in the summer months, changes fuel consumption (demand). Although hydrogen serves as energy storage, the ideal is a balance between production and demand, to avoid difficulties from large stored quantities. System analysis will advise on the economic amount of hydrogen production that will fully cover fuel demand needs. Retrofitting vessels to use hydrogen fuel cells or combustion engines is technically feasible but requires significant modifications to power systems, storage infrastructure, and safety measures.

The findings align with existing research on the potential of hydrogen as a sustainable maritime fuel. Studies on offshore renewable energy platforms highlight their potential for green hydrogen production, particularly in regions with abundant wind and solar resources [45]. The energy requirements for hydrogen production and compression are consistent with industry benchmarks, emphasizing the dominance of electrolysis in energy consumption [44].

However, this study adds value by focusing on the specific challenges and opportunities of integrating hydrogen propulsion in small island communities, where energy security and space constraints are critical considerations.

The transition to hydrogen-based maritime transport requires supportive policies and regulatory frameworks. Harmonizing standards for hydrogen production, storage, and safety across maritime jurisdictions is essential. Financial incentives, such as grants and subsidies, can encourage investment in offshore renewable energy platforms and hydrogen infrastructure. Training programs for local stakeholders and crew members are needed to ensure the safe and efficient operation of hydrogen systems. Policies should promote the use of green hydrogen and penalize high-emission fuels to accelerate decarbonization.

This study has several limitations. The analysis is based on a hypothetical platform and vessel, requiring real-world validation. Energy requirements and costs are based on theoretical models and industry averages, which may not reflect local conditions. The findings are specific to small passenger vessels and may not be directly applicable to larger ships or longer routes.

Future research may focus on improving the efficiency and cost-effectiveness of hybrid renewable energy systems for hydrogen production. Exploring technologies that bypass desalination to reduce energy requirements. Implementing pilot projects to test and refine hydrogen propulsion systems in small island settings. Assessing the environmental and economic impacts of hydrogen production and use over the entire lifecycle.

6. Conclusions

The study highlights the transformative potential of offshore green hydrogen production in achieving decarbonization goals for maritime transport. By leveraging abundant renewable energy resources in the marine environment, small islands can, reduce their dependence on imported fossil fuels, lower emissions and air pollution, and enhance energy security and resilience against global fuel price fluctuations. This approach aligns with global efforts to combat climate change and transition to sustainable energy systems.

This study contributes to the growing body of knowledge on sustainable maritime transport by providing a detailed analysis of the energy, economic, and environmental aspects of green hydrogen production and use in small island settings. It is also, demonstrating the feasibility of integrating offshore renewable energy platforms with hydrogen propulsion systems. Actionable insights are offered for policymakers, industry stakeholders, and researchers working on decarbonizing maritime transport.

The findings have significant implications for policy and practice. Governments and international organizations should develop supportive policies and regulatory frameworks to promote offshore renewable energy and hydrogen technologies. Financial incentives, such as grants and subsidies, can encourage investment in green hydrogen infrastructure. Training programs for local stakeholders and crew members are essential to ensure the safe and efficient operation of hydrogen systems. Policies should prioritize green hydrogen and penalize high-emission fuels to accelerate the transition to sustainable maritime transport.

To realize the potential of green hydrogen in maritime transport in small islands, pilot projects may be implemented, to test and refine near coast renewable energy platforms and hydrogen propulsion systems in small island communities. Investment in research and development to improve the efficiency and cost-effectiveness of hydrogen production, storage, and use. Foster collaboration between governments, industry, and local communities to address technical, economic, and regulatory challenges. Raise awareness about the benefits of green hydrogen and its role in achieving decarbonization goals.

The study's findings have broader implications for the global maritime industry and small island communities. Hydrogen-based propulsion can significantly reduce GHG emissions and contribute to global climate goals. Localized hydrogen production enhances energy independence and resilience against fuel price fluctuations. Transitioning to green hydrogen supports the socio-economic development of small islands by creating jobs and reducing energy costs. The proposed solutions can serve as a model for other coastal and island regions seeking to decarbonize maritime transport.

The future of sustainable maritime transport lies in the widespread adoption of green hydrogen and renewable energy technologies. Continued innovation, policy support, and industry collaboration are essential to overcome the technical and economic challenges associated with hydrogen production and use. By investing in these solutions, small island communities can lead the way in the global transition to a low-carbon future, demonstrating the viability of hydrogen as a sustainable maritime fuel.

This study underscores the critical role of green hydrogen in decarbonizing maritime transport, particularly in small island communities. By harnessing the power of offshore renewable energy and hydrogen technologies, these regions can achieve energy security, reduce emissions, and contribute to global sustainability goals. The journey toward a hydrogen-powered maritime industry is challenging but achievable, offering a cleaner, more resilient future for all.

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