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Hydrogen as a Viable Energy Source in Maritime Coastal Transport

Summary

Coastal areas and islands, particularly due to their unique geographical and climatic conditions, are among the most vulnerable to the effects of climate change. Achieving decarbonization goals requires profound and innovative changes. In this context, islands stand out as ideal locations for experimenting with the green transition, where new ideas and alternative approaches can be tested. A special focus is placed on hydrogen (H2) based technologies, which are emerging as promising allies in generating renewable energy on islands, including energy storage aspects. Considering the abundance of sunlight, for example on remote Adriatic islands, there is significant potential for combining renewable sources and hydrogen-based technologies in producing “green hydrogen” using solar technologies. Hydrogen production using solar energy, as a clean energy source, can be carried out directly or indirectly through the use of solar energy for water electrolysis. The rapid development of this technology raises questions about the level of political support needed for its expansion and encouragement.
The growing concern of society and political actors regarding greenhouse gas emissions and air pollution is increasingly directing attention to emissions from the maritime sector. Hydrogen is considered as a potentially clean fuel for the maritime sector, with the possibility of production from renewable energy sources, despite the maritime sector’s currently limited experience with this fuel. The use of alternative fuels in maritime transport has been at the center of intense research and debate over the past twenty years, exploring numerous possibilities for different types of ships. Challenges associated with pollutant emissions in ports and coastal areas by ship engines have been highlighted as key drivers for the exploration and application of innovative and alternative fuels in the maritime transport sector.

Keywords: green hydrogen, maritime coastal transport, renewable energy sources

1. Introduction

In the context of challenging climate changes, the need for innovative solutions in the clean energy sector is becoming increasingly pronounced, requiring approaches that transcend traditional methods. Islands represent unique laboratories for exploring new energy solutions, offering insights into possibilities for equitable, inclusive, and sustainable energy systems. In addition to facing engineering challenges such as energy supply instability and space utilization limitations, island communities have the opportunity to explore a wide range of renewable energy sources such as solar, wind, and tidal energy, despite the current prevailing dependence on fossil fuels. The development of offshore energy projects is becoming an increasingly attractive response to limited land space, especially in island communities.

The issue of energy storage is crucial for the sustainability of these innovative energy solutions, traditionally relying on expensive options like pumped hydro storage or conventional batteries. Innovations in energy storage technologies, including advanced batteries and hydrogen systems, are beginning to offer alternative solutions. Notably, islands like the Canaries and Madeira have already invested in energy storage infrastructure, with varying results. (1), (2), (3).

From a technical perspective, the production and use of hydrogen represent a key component in the transition towards cleaner energy, with various methods of hydrogen categorization forming the so-called hydrogen color spectrum. This paper focuses on green transitional pathways for hydrogen production, excluding carbon-based fuels. Due to the limited CO2 emissions from island emitters, the direct impact on the carbon-based solar energy industry is minimal (4).

The use of pure hydrogen or hydrogen blends with conventional fuels presents a sustainable alternative for powering ships that are essential for connecting islands to the mainland, utilizing technologies such as fuel cells (FC) and internal combustion engines on ferries. Recently, the first commercial fuel cell ferry using pure hydrogen was built and approved for use. Fuel cells, as the most environmentally friendly method of producing energy from hydrogen, offer numerous advantages, including negligible emissions such as NOx, minimal noise, and low maintenance costs. However, challenges such as hydrogen leakage and the long-term reliability of PEM fuel cells require further research. Direct use of hydrogen can reduce energy losses that occur during the conversion process, thereby optimizing energy efficiency (5).

To contribute to global efforts in reducing greenhouse gas emissions, governments worldwide are developing diverse policies and strategies aimed at promoting clean hydrogen-based projects. Fundamental aspects of these policies include establishing guidelines and standards that facilitate the efficient demonstration and commercial use of hydrogen technologies, with careful consideration of the legislative framework to ensure harmonization at local, regional, national, and international levels. The specificity of policies focused on hydrogen lies in their aim to connect with existing industrial sites, known as ‘hydrogen clusters,’ thereby supporting the energy transition and its impact on various sectors, including mobility and construction. Coastal industrial clusters attract special attention due to their proximity to planned large offshore wind farms, and the potential transformation of port areas into hydrogen hubs, which would reduce emissions in maritime transport and port activities. Islands offer ideal conditions for testing such initiatives (6).

In this context, the European Commission, in line with the Renewable Energy Directive, has introduced detailed rules through two delegated acts that define hydrogen produced from renewable sources within the EU. These acts are a key part of the comprehensive regulatory framework for hydrogen in the EU, which includes financing for infrastructure, state aid rules, and legal targets for the use of renewable hydrogen in industry and transport. The aim of these acts is to ensure that all renewable fuels of non-biological origin are produced exclusively using renewable electricity, thereby providing regulatory certainty to investors as the EU aims to produce 20 million tonnes of renewable hydrogen, as outlined in the REPowerEU plan.

The first act specifies the conditions under which hydrogen and related fuels can be considered renewable fuels of non-biological origin, emphasizing the 'additionality' principle that requires hydrogen electrolyzers to be connected to new renewable energy capacities. This approach aims to ensure that hydrogen production contributes to increasing the renewable energy available to the grid, encouraging decarbonization without additional burden on electricity production. The second act establishes a methodology for calculating greenhouse gas emissions throughout the entire lifecycle of renewable fuels, including everything from production to end consumption, ensuring transparency and consistency in assessing the environmental impact of renewable hydrogen and its derivatives (7).

2. Hydrogen utilization in short sea shipping RO-RO and RO-PAX vessels

The application of hydrogen as fuel in Norwegian maritime transport has been explored by various researchers (8), (9). These studies have provided deeper insights into the optimal dimensions and types of vessels for hydrogen use. Notably, research in Norway and Croatia concerning the use of new fuels in maritime transport has been highlighted. For instance, in Norway, a fuel cell passenger ship named Hydra has been designed, with its imminent use expected (10). For the purposes of short sea navigation, leading engine manufacturers are experimenting with combinations of hydrogen and other fuels to increase the efficiency of four-stroke engines (11).

A significant topic of discussion within the maritime sector pertains to the use of hydrogen on ships designed for short sea routes, known as Roll-on/Roll-off (Ro-Ro) or Roll-on/Roll-off Passenger (Ro-Pax) vessels (12), which are frequently utilized in the Adriatic Sea. Ro-Pax ships are a type of ferry that falls under the broader category of Ro-Ro vessels, equipped for transporting various kinds of cargo and vehicles, allowing for horizontal loading and unloading. In addition, Ro-Pax ferries are specifically designed to carry passengers along with a diverse range of vehicle types.

The use of hydrogen as fuel in short coastal ferry routes offers a range of advantages. For example, the limited amounts of fuel required on board facilitate operational procedures and reduce the time needed for refueling. Since Ro-Ro and Ro-Pax vessels are engaged in scheduled line traffic according to a predetermined schedule, hydrogen needs can be more accurately planned compared to other types of vessels such as container ships or fishing boats, where hydrogen could also be applied.

Addressing the challenge of sustainable transport includes the maritime sector, where studies encompassing Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) have been conducted. The results of these studies indicate that hydrogen presents a promising alternative to fossil fuels in maritime transport. However, the high costs of hydrogen and fuel cell technology currently pose a major barrier.

Existing research has highlighted the potential of liquid hydrogen (LH2) in the maritime sector, stating that LH2 could replace fossil fuels provided there is a reduction in the costs of LH2, its handling and storage components, and addressing the issue of infrastructure shortage. Likewise, for the successful implementation of LH2-based technologies, their adaptation to specific applications is necessary, including types of ships and port sizes (11).

Ro-Ro and Ro-Pax ships are specialized vessels designed for the transport of vehicles such as cars, trucks, and buses, facilitating their easy loading and unloading. Hydrogen is considered as a fuel option for these ships, either through combustion in conventional internal combustion engines or through use in fuel cells to generate electrical energy that powers the ship's engines. Switching Ro-Ro ships to hydrogen could significantly reduce emissions during navigation and port stays, thereby contributing to the reduction of environmental impact and meeting stricter emission standards.

However, using hydrogen as fuel for Ro-Ro and Ro-Pax ships brings certain challenges. Shipping companies may face difficulties in justifying the investment in expensive fuel cell technology. Additionally, the limited availability of fuel cells that can meet the needs of ships with a total power greater than 10 MW presents an additional challenge. Issues with infrastructure and hydrogen supply chains can further complicate the refueling of ships at sea or in port. Even if refueling infrastructure were available, the time and procedures required for refueling could limit the practicality of using hydrogen.

The technical feasibility of adapting some Ro-Ro/Ro-Pax ships for hydrogen system use may be uncertain due to their dimensions, architecture, and the potential for decreased cargo capacity. Regulatory demands, encompassing safety protocols and emission norms, present further obstacles during the hydrogen technology development phase. Moreover, training the crew to manage hydrogen systems and formulating suitable maintenance practices are essential requirements.

To avoid a complete retrofit of ships for hydrogen propulsion, an alternative approach could be the partial integration of hydrogen technologies into Ro-Ro/Ro-Pax vessels. This could involve installing hydrogen fuel cells or similar systems to power specific ship operations or devices. For instance, instead of converting the entire main propulsion to hydrogen, it's possible to install fuel cells that would provide energy for secondary systems like lighting, heating, or air conditioning. This approach can offer benefits such as lower energy consumption and reduced emissions, along with improved ship efficiency. Moreover, such partial adaptation could be more cost-effective and technically less demanding compared to a full conversion of the ship to hydrogen propulsion (11).

3. Islands and coastal areas

Islands have a long history of being used as areas for political experiments, especially in the realm of green technologies (13), with growing interest recently in their role in implementing solutions related to the energy transition (14). Due to their small size, islands provide relatively limited and 'safe' spaces for testing new technological solutions. Electrical grids on islands are often sensitive, and energy supply stability can pose a challenge, thereby encouraging the development of new energy initiatives.

Islands are often situated at the edges of existing infrastructure and networks, making them ideal for innovative projects. They tend to enjoy considerable political and regulatory freedom, which allows for the application of exceptions and derogations from some standards (including those of the EU), and the testing of solutions that would not be applied within broader legal frameworks.

This unique position of islands, at the transition between sea and land, opens up numerous opportunities for innovation. For various reasons, islands are often compelled to innovate, making them ideal places for the development and application of new technologies (15).

The North Sea has become an epicenter of innovation in the offshore renewable energy sector, with islands like Helgoland in Germany playing key roles in the development of offshore wind farms. Additionally, islands in the Aegean, Mediterranean Sea, and the wider Atlantic, including the Azores, have made significant contributions to the energy transition through involvement in leading projects (16). Projects like SMILE, supported by the EU, have connected a series of remote islands such as Samsø, Madeira, and Orkney into an innovation network. The development of the idea of islands as laboratories has evolved into the concept of artificial islands in the North Sea, envisioned for renewable energy generation and hydrogen. Initiatives from Denmark, Belgium, the Netherlands, and the United Kingdom include plans for creating such energy islands, which would utilize both existing islands like Bornholm and new artificial structures for energy storage and associated infrastructure, exploring options for hydrogen production and storage as well (15).

In parallel, the island of Elba, located near the Italian coast in the Tyrrhenian Sea, is connected to the mainland by numerous Ro-Ro ferry lines to the port of Piombino. With a winter population of about 31,000 inhabitants, which increases to over 300,000 in the summer, the Piombino-Elba ferry route becomes one of the busiest in Italy and the Mediterranean. The ferry journey takes about an hour, covering a distance of approximately 27 km, making this route ideal for the application and exploration of hydrogen-powered vessels. This synergy between the development of energy innovations in the North Sea and the potential of the island of Elba for the application of hydrogen technologies illustrates how different geographical contexts can contribute to a broader spectrum of the energy transition (11).

4. Hydrogen retrofits in coastal navigation and bunkering opportunities

When considering the retrofitting of existing RO-RO vessels for short coastal navigation, often seen in the Mediterranean and Adriatic, for hydrogen use, there are three main strategies:

1. Complete replacement of all engines with fuel cells, representing a full retrofit.
2. Replacement of only auxiliary engines with fuel cells, considered a partial retrofit.
3. Use of auxiliary engines replaced with fuel cells only, also a partial retrofit.

Among these options, the third one is unique in that it enables zero emissions in port, thanks to the ability of fuel cells to provide all the necessary energy. In the context of hydrogen research, fuel cells are often the preferred choice for propulsion over traditional engines. Until recently, projects focused on hydrogen engines were not included in EU programs coordinated by Hydrogen Europe. However, Hydrogen Europe has recently revised its stance towards hydrogen engines, especially in the context of their use for power generation and propulsion in demanding conditions, opening up the possibility of their application across a wide range of heavy-duty loads, both on land and at sea. Nevertheless, hydrogen engines are less efficient compared to fuel cells, leading to higher hydrogen consumption - a key factor when tank capacity and refueling are major obstacles. Therefore, fuel cells are often the more logical choice. Although the use of engines could negatively impact tank capacity and refueling time, potentially worsening outcomes.

There are three main refueling methods for Ro-Pax ferries operating short coastal routes, including:

- Shore-to-ship refueling methods,
- Ship-to-ship, and
- Truck-to-ship.

The common practice for conventional ships is ship-to-ship refueling, where bunker vessels dock alongside the ferry usually during the loading or unloading process. Refueling in port can involve simply connecting a pipeline to the ferry or a complete hydrogen station with storage capabilities.

Alternatively, refueling can be performed directly from trucks delivering compressed hydrogen, or through the exchange of containers. The optimal setup of the refueling station will depend on its size and the amount of hydrogen that needs to be delivered. The approach to refueling varies depending on the operational range of the ships, especially when it comes to maneuvering in port.

Truck-to-ship refueling is a common practice today where the truck remains on the ferry throughout the entire refueling process, and the ferry's activities continue uninterrupted. Direct refueling from a hydrogen station at the dock represents a convenient option, although it is not feasible for all ports and ferry lines (17).

Using multiple refueling lines can solve the issue of prolonged charging times, but this requires additional equipment such as compressors and coolers, which increases energy consumption. Having multiple refueling points for smaller ships can exacerbate safety challenges and does not facilitate the refueling process, as managing multiple bunker vessels and trucks at the refueling site or setting up multiple hydrogen stations requires significant infrastructural changes and additional costs. For these reasons, multiple refueling points for an individual ferry are not considered an efficient or suitable solution.

It's important to note that the conventional refueling of diesel fuel on such ships is usually carried out from a bunkering ship on the seaward side during loading and unloading or by tanker, which increases the safety of the refueling process without interrupting service. Introducing refueling stations along the docks requires significant infrastructure development efforts and can carry safety risks, especially due to the traffic of passengers and vehicles that mainly occurs on the dockside (11).

The SAE J2601 standard regulates the hydrogen refueling process, setting efficiency requirements for stations that use gaseous hydrogen under various operating conditions. These standards are crucial for ensuring safe refueling, given that rapid refueling can lead to gas heating, posing potential risks. The refueling protocol for heavy-duty vehicles using gaseous hydrogen provides for a minimum flow rate of 3.6 kg/min for standard refueling and up to 7.2 kg/min for fast refueling (18).

Nighttime refueling imposes specific requirements, including the presence of several crew members on board during the night, ready to intervene if necessary. This need for nighttime operations represents additional costs for ferry operators due to the requirement for night shifts and additional crew, without direct return on this extra investment.

One way to reduce the need for nighttime refueling could be to increase the number of refuelings during the day, given that ferries make multiple trips daily. This could optimize operational efficiency and reduce the need for nighttime crew operations, thereby lowering operational costs and enhancing safety

4.1. Comparable examples as a demonstrative indicator for croatian outer islands

In the context of global efforts for decarbonization and the transition towards sustainable energy sources, significant attention is being paid to harnessing renewable sources, such as solar energy, for the production of green hydrogen. Croatian islands, with their abundance of sunlight and favorable geographical position, offer exceptional opportunities for the development of such projects. This section considers the potential of the islands of Vis, Hvar, Korčula, and Lastovo, with a special focus on Vis, where conditions for solar energy production are particularly favorable.

The island of Vis, with the highest average annual solar irradiation values according to available irradiance maps (Figure 1), is under consideration. The high irradiance values not only indicate an exceptional potential for electricity production through photovoltaic systems but also create a basis for considering Vis as an ideal location for the production of green hydrogen. Green hydrogen, produced through the electrolysis of water using electricity obtained from renewable sources, represents a key component in efforts to reduce carbon dioxide emissions and transition towards clean energy.

Although Hvar, Korčula, and Lastovo are also islands with high potential for harnessing solar energy, a detailed analysis and comparison with Vis show that Vis has advantages, particularly in the context of the availability of space suitable for the installation of large solar power plants and favorable weather conditions. Such conditions enable continuous and efficient electricity production, which is crucial for stable green hydrogen production.

Considering these advantages, it is possible to establish infrastructure on Vis that would enable the production and storage of green hydrogen. Such a project would not only contribute to the island's energy self-sufficiency but also open up opportunities for creating "green corridors" for maritime transport, where ferries and ships could use hydrogen as a clean energy source.

This section lays the groundwork for further exploration and development of green hydrogen projects on the islands, with a focus on Vis as a leading example. A detailed analysis of the potential, challenges, and opportunities for implementing such projects will be crucial for future initiatives towards a sustainable energy transition on the Croatian islands (19).

The Vis solar power plant represents a significant step forward in harnessing renewable energy sources on Croatian islands, with a special focus on promoting sustainability and energy independence. Located at Griževa glavica, the plant is situated 3.6 kilometers southwest of the town of Vis and 4.8 kilometers east of Komiža, strategically positioned to maximize solar irradiation on the island.

Spanning an area of 5.5 hectares, the Vis Solar Power Plant has an installed capacity of 3.5 megawatts, with a total of 1,600 photovoltaic (PV) modules, each with a power of 340 Wp, making up a total of 11,200 modules. This impressive infrastructure enables the production of a significant amount of electrical energy directly from sunlight, thereby reducing dependency on fossil fuels and promoting a cleaner, greener future for the island.

Alongside the solar power plant, a crucial part of the infrastructure is the battery storage located immediately next to the plant. With a capacity of 1.44 MWh and a power of 1 MW, the battery system plays a vital role in balancing the island's electrical system. By providing balancing services and maintaining grid stability, this system ensures a reliable and continuous supply of electricity, even in conditions of varying production or consumption.

The implementation of the Vis Solar Power Plant and the accompanying battery storage exemplifies how modern technology and renewable energy sources can be integrated into the energy ecosystem of an island, providing sustainable and innovative solutions to energy challenges. Through such projects, Vis and other Croatian islands can become leaders in the transition towards a greener and more sustainable future, laying the groundwork for the broader application of renewable sources and energy storage technologies in the region and beyond. (20)

Croatian islands, such as Lastovo and Vis, have a significant potential for green hydrogen production thanks to high levels of solar irradiation and available spaces for solar panel installation. Hydrogen production on these islands could be key for supplying the liner shipping industry, especially Ro-Ro and Ro-Pax vessels, with clean fuel. By introducing hydrogen refueling stations on the islands, and in parallel on the mainland, it would enable ships to use sustainable fuel throughout their entire route, thereby reducing greenhouse gas emissions and contributing to global sustainability goals.

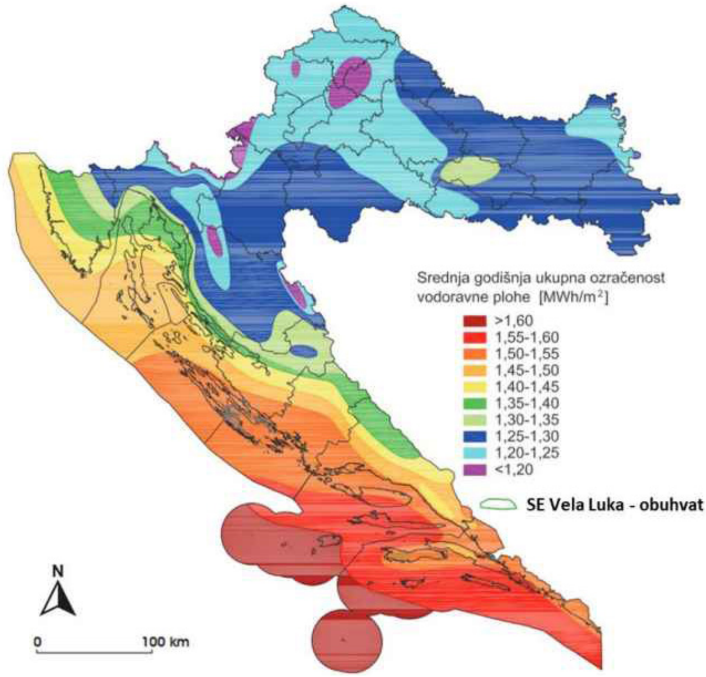

Figure 1. Average Annual Total Irradiance of Horizontal Surfaces (MWh/m²) (Energy Institute Hrvoje Požar)

4.2. Current projects

Currently, in political discourse, islands are being assigned the role of pioneers in the development of offshore wind farm industry, while simultaneously adopting new technologies for energy storage and distribution. The main challenge for islands is to expand their role and capacities to support a wider range of innovative energy solutions, including technologies based on solar energy as a crucial segment.

It is observed that innovation projects encompassing hydrogen and renewable energy sources vary among islands in terms of ambitions, available resources, and strategic approach. Particular interest lies in exploring synergies that go beyond mere energy storage produced on islands through hydrogen, emphasizing the production of green hydrogen using locally produced renewable electricity. Projects like SEAFUEL and GREEN HYSLAND reflect a high level of ambition in this area. The SEAFUEL project aims for local production of green hydrogen which would then be used as fuel for local public transport fleets and vehicles rented to tourists, representing an innovative application in mobility. Such an approach increases the visibility of hydrogen technologies among the public, including tourists in Tenerife, providing them with an opportunity to experience firsthand how their mobility needs are met through a combination of renewables and hydrogen, thereby encouraging public acceptance of hydrogen technologies and increasing prospects for new projects. This project is ambitious not only at the local level but also in creating a transatlantic 'innovation network' that includes islands in Ireland and Portugal.

On the other hand, the GREEN HYSLAND project initially focuses on Mallorca in Spain, with the goal of creating a comprehensive 'hydrogen ecosystem' on the island. The project will utilize solar energy to produce electricity, a portion of which will be used to produce green hydrogen. This hydrogen will then be used as an energy carrier across the island, including its injection into Mallorca's natural gas system, further integrating the use of renewable sources into the island's energy system.

4.3. Institutional support for projects related to renewable energy sources, hydrogen, and solar energy solutions on islands analyzed through the Multi-Level Perspective (MLP) framework.

The use of the Multi-Level Perspective (MLP) theoretical framework has been applied to the analysis of technological transitions to understand the ways in which public policies can encourage or, conversely, hinder the role of islands as key sites for exploring the potential of solar energy within the broader context of renewable energy sources and hydrogen in production, storage, and distribution. The MLP approach highlights that significant technological changes arise from the synergy of trends at different societal levels that come together to create a critical mass for change. Such changes require a period due to the need for reinforcement and a certain degree of alignment, which is rarely planned or anticipated in advance. Actors at various levels may attempt to change perceptions, engage in power struggles, lobby for favorable regulations, and compete with each other. Therefore, system transitions should encompass all levels of the system. The MLP approach identifies three key dimensions for locating drivers of change: niche innovations, regime structures, and the broader socio-technical landscape.

At the foundational level, there are niche innovations, which serve as breeding grounds for new technologies, often in the form of start-up companies, research laboratories, and even individual inventors or pilot projects. A core insight from the MLP approach is that innovators within these initiatives often require a certain level of protection from external competition, initial technological failures, and high costs, which is typically provided through integration with larger organizations or projects, often with the support of significant subsidies and sometimes special exemptions and regulations. Such protection often involves key actors within the broader socio-technical context, such as governments, regulatory bodies, and network operators, who provide support, financial resources, and technical assistance. In this context, islands particularly stand out as niche innovations of interest for observation..

It's important to highlight that within innovation initiatives, we find not only standalone technological innovators. There are competing or alternative initiatives representing different technological approaches, where users and consumers are key participants who can either accept and support a new technology or reject it as too expensive or impractical for various reasons. It's also crucial to recognize that social sciences consider islands key sites for energy transition, particularly emphasizing the importance of how actively local communities are involved in the development of new energy infrastructure and whether such investments align with local needs. Local support and approval are essential for success, especially in the context of planning. Previous research highlights that well-designed demonstrations and implementations of projects related to hydrogen or similar initiatives among various stakeholders can foster a sense of belonging and ownership among public authorities and citizens (23).

Projects on islands need to be integrated with the broader network of opportunities and innovations to avoid being perceived only as isolated and unusual endeavors. Therefore, when evaluating islands as sites for accelerated green transition, it's crucial to assess the extent to which islands exhibit dynamic activity within innovation initiatives. Besides specific pilot projects exploring new technologies, these initiatives should have the support of the local community and the engagement of local authorities. It's also important to evaluate the level of protection provided by subsidies and specific regulations.

At the regime level, we find those who shape the rules and create the framework within which technologies develop and are managed, leading to complex and intertwined socio-technical systems. This includes, for example, national electrical grid systems, regulatory systems for energy companies and suppliers, and various fiscal and tax policies related to the energy sector. In today's globalized world, established regimes are not limited to the national level, as there is a range of complex international systems that govern technologies in various areas. Within the European context, the European Union plays a key role at the regime level, setting broad guidelines for the energy market while actively participating in shaping broader policy goals, especially in relation to climate change and energy transition.

For instance, in Greece, islands have been recognized as a key factor in the transition to renewable energy sources and in stimulating the country's economic growth. Accordingly, Greece's ten-year development plan from 2010 pays special attention to addressing the challenges faced by islands. One of the proposed solutions is establishing connections between the islands and the mainland through electrical grids. When this is not feasible due to financial or technical constraints, the development of independent systems for producing energy from renewable sources is planned. Furthermore, according to data from the Greek Regulatory Authority for Energy in 2014, there are several island systems that are not connected to the main mainland electricity grid. These island systems, which are not powered from the central electricity grid, consist of thirty-two standalone systems and groups of islands and are therefore focused on developing self-sufficient solutions for energy supply (24).

Existing established frameworks and policies may not be sufficiently flexible for the specific situations on islands, necessitating their adaptation or even deviations. Policies supporting energy initiatives on islands sometimes require special tailoring because some energy projects have resulted in technological failures, increased energy prices, and no visible improvement in grid stability. Energy projects on islands will likely need significant subsidies and other forms of support, such as guaranteed favorable grid connection tariffs, in the short term. A common weakness in policies is the lack of willingness to adequately finance or regulate energy storage elements within planned energy projects on islands. Also, connecting cables to mainland grids are crucial where available. Given the complex governance structures of islands, it's important to ensure that different levels of regulation (European, national, regional, island) work in synergy, rather than contradicting each other (24).

The key understanding here is that individual islands embrace innovative energy initiatives as part of a broader regional, national, and international context—a system of policies, subsidies, and decisions that shape energy policy and fuel choices. The crucial factor is the extent to which any established framework sends a clear signal of support to islands as centers of energy innovation.

Established frameworks and policies are often not sufficiently adaptable to the challenges faced by islands, necessitating their adjustment or specific deviations. Energy initiatives on islands may require unique policies due to the risk of technological failures, higher energy costs, and insufficient grid stability. In the short term, these and similar projects typically need significant subsidies and special incentives, such as preferential tariffs. There's also a need for adequate financing and regulation for energy storage elements, according to Tsagkari and Jusmet. Connectivity to mainland grids where possible is important. Governance structures on islands must ensure alignment of various regulatory levels to avoid conflicts.

It's crucial to understand that islands, as sites for innovative energy projects, operate within the broader framework of regional, national, and international policies. The signal that established frameworks send in terms of supporting islands as leaders in energy innovation is significant.

It's evident that the national level plays a pivotal role within established frameworks, and in this case study, the energy policy of Spain, for example, stands out for its unique features. While Spain is already achieving significant electricity production from renewable sources, further investments are required to reach the national goal of increasing the share of renewable energy to 74% of total electricity production by 2030. In 2016, Spain was importing nearly 1.3 million barrels of oil per day, leading to a high energy dependency of 73.9% in 2017, significantly above the EU average (15).

The Canary Islands represent a unique case within the Spanish energy context due to their isolation from mainland grids, relying on six separate island grids instead of connectivity to the main grid. They predominantly depend on conventional oil and gas power plants, and Red Eléctrica de España plays a key role in maintaining the stability of their electrical systems, focusing on costly energy storage technologies. Despite the economic challenges of lower economies of scale on the islands, Spanish policy ensures unique electricity tariffs within its jurisdiction, thereby subsidizing energy consumption on the islands by mainland consumers. The Canary Islands enjoy a certain level of autonomy in energy matters, with their own energy plan and a recently adopted Sustainable Energy Strategy, funded through national and EU funds (25).

At the global level, structural and societal changes such as globalization, technological innovations, climate change, and the COVID-19 pandemic act as macro-drivers that influence energy policies and transitions. These global events create pressures and send signals that can either stimulate or slow down energy transitions, underscoring the need for sustainable energy sources in combating climate change.

Trends within the broader socio-technical context rarely initiate changes on their own; typically, the engagement of actors within established frameworks and innovation initiatives in innovations that gain momentum due to events at the broader societal level is necessary. Much depends on the timing: if pressures from the broader socio-technical context arise while innovations within niche innovations are still in their early stages, the path to transition will be different than in a situation where innovations are fully developed. However, actors within niche innovations and established regimes can consciously form alliances that anticipate pressures from the broader socio-technical context or protect niche innovations until favorable conditions for their wider adoption are created. A key element of such a process is pilot projects that test new technologies in a pre-commercial phase. This paper deals with a case study that illustrates the extent to which some of the positive trends identified through this approach have been recorded:

- Engagement and participation of local communities within innovation initiatives;
- Implementation of protective strategies through financial support and legal regulations within innovation projects;
- Collaboration with supporting structures at the domestic and European level through affirmative policies, regulations, and access to funding;
- Interaction with broader societal trends, with a particular focus on the urgent need for energy sources that do not contribute to climate change;
- Focus on research and development of innovations in the technological sector, including solutions based on solar energy, aiming for breakthroughs towards future possibilities.

4.4. The Canary islands example

This example is based on financial support provided by EU agencies through the INTERREG program, aimed at promoting interregional cooperation between areas sharing similar challenges and opportunities. The SEAFUEL project, part of the

INTERREG Atlantic Area and focused on the theme of "Resource Efficiency," started in December 2017 with the goal of demonstrating the feasibility of using local natural resources on islands to power vehicles with green hydrogen, thereby eliminating emissions. The project focused on isolated islands such as the Canary Islands, where fuel import costs significantly burden regional and national budgets. By leveraging local resources, the aim was to make these islands sustainable and self-sufficient, eliminating the need for fuel or energy imports.

Initially, the project encountered challenges due to limited interest in hydrogen technologies in 2017 and 2018, despite global concerns about climate change, the Paris Agreement, and IPCC reports. The lack of significant incentives for renewable energy and fuels made it difficult to attract stakeholder attention, especially on smaller islands with limited industrial activities. Larger industries considered the market niche, with no prospects for a quick return on investment, resulting in a lack of interest in participating in the project. The shift in perception, interest, and investment opportunities was ultimately driven at the European level, with strong encouragement for the use of renewable energy sources and hydrogen as means to achieve climate goals set for 2030 and 2050. A turning point for hydrogen was the announcement of the EU Hydrogen Strategy in 2020, which laid the groundwork for the "Fit for 55" plans aimed at achieving net-zero greenhouse gas emissions in the EU by 2050. Subsequently, many EU member states, including Spain, introduced their national hydrogen strategies, mostly focused on decarbonizing continental industrial sectors. In Spain, the goal of the national strategy was to replace 25% of industrially used hydrogen with green hydrogen by 2030. This approach posed a new challenge for the implementation of hydrogen technologies in isolated locations such as the Canary Islands, highlighting the need for the development of specific strategies tailored to the unique challenges faced by island communities. Figure 2 illustrates a demonstration facility of the project located on Tenerife, one of the Canary Islands, showing how the facility is used for practical purposes.

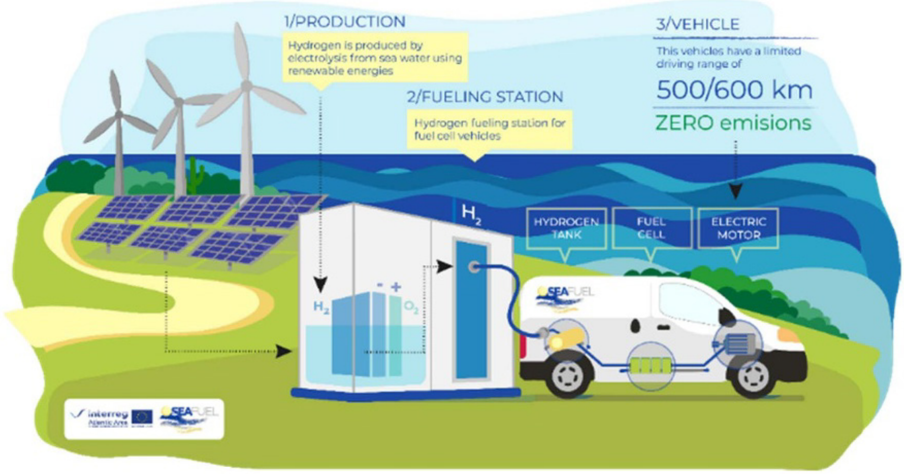

Figure 2. Schematic representation of the SEAFUEL project utilizing solar energy to power a hydrogen refueling station using seawater, and using that fuel for a vehicle fleet.

The choice of location was crucial for demonstrating the feasibility of producing green hydrogen solely from solar sources and seawater. The SEAFUEL facility represents the world's first such installation combining hydrogen production and a refueling station. ITER's facilities are equipped with over 30 MW of solar panels and two desalination plants that provide water for the facility's needs. ITER also manages a wind farm and is responsible for maintaining a series of solar and wind farms across Tenerife. Diesel vans are used for maintenance, and their replacement with battery electric vehicles is complicated due to hard-to-reach locations with steep access roads. Hydrogen fuel cell vehicles (FCEVs) or electric vehicles with extended range represent a practical alternative, enabling extended range utilization using hydrogen and fuel cell power to drive the vans.

The main obstacles to the project were directly related to the limited market on Tenerife, illustrating how the geographical position of an island can pose a challenge. For example, automobile manufacturers were not interested in delivering fuel cell electric vehicles (FCEVs) for the project due to high transportation costs and the establishment of specialized services on the island. However, as the project progressed and interest in hydrogen technologies grew, Hyundai Canarias and Toyota Spain joined the project, providing Hyundai Nexo and Toyota Mirai models. These vehicles became key to SEAFUEL's second goal focused on tourism, considering that tourism accounts for over 75% of the Canary Islands' economy. Given the significant share of transportation in CO2 emissions, the project explored tourist interest in FCEV vehicles through surveys and test drives, using the large car rental market on the islands as a platform for testing new technologies.

The SEAFUEL installation also encountered obstacles, particularly due to the lack of local experience with hydrogen technologies, which delayed obtaining the necessary permits. This issue was resolved through collaboration and sharing documentation and knowledge with partners from Europe. Additionally, the isolation of the Canary Islands and the special tax and import system posed further challenges, especially in light of Brexit complicating imports from the UK. Finally, initial technical problems with the installation required bringing in experts from Europe, further increasing maintenance and repair costs.

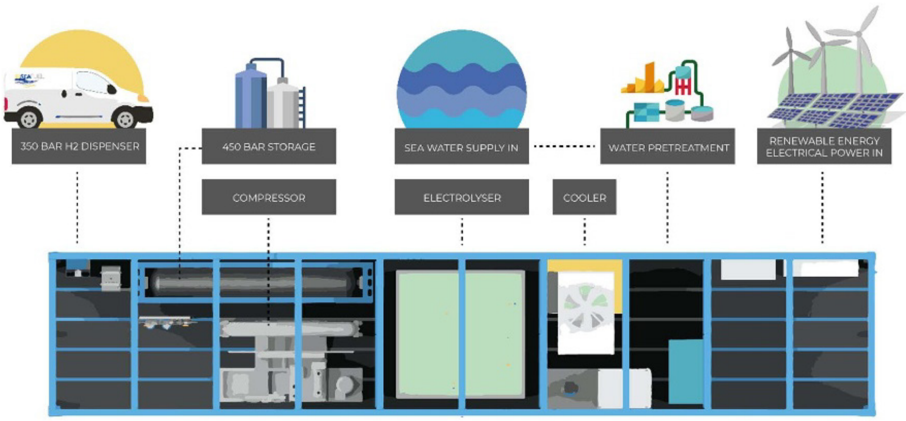

Figure 3. Hydrogen production at the SEAFUEL refueling station on Tenerife. Reproduced with permission from SEAFUEL. Image author: Lucia Villalba

The SEAFUEL project aimed not only at technical demonstration but also at highlighting the specific needs of islands in terms of achieving climate goals and decarbonizing the transport sector. While electric vehicles are a desirable option for smaller vehicles, provided the electrical grid can support the growing demand and integration of renewable sources, the market for fuel cell electric vehicle (FCEV) rentals presents an interesting alternative. This could encourage local hydrogen production and the development of refueling infrastructure, supported by the tourism sector, allowing tourists to use FCEV vehicles and thereby creating a new market for used vehicles given the short lifespan of rental vehicles. For public transport, especially on Tenerife where terrain and infrastructure limit the use of electric buses, hydrogen represents a sustainable option. SEAFUEL has developed a specific hydrogen roadmap for Tenerife, highlighting the unique challenges and opportunities of the island. Collaboration with regional authorities is key to ensure that recommendations from this roadmap can be considered and potentially integrated into the island's plans for sustainable energy and climate action (15).

4.5. Example of retrofitting RO-RO, RO-PAX ships for Elba island

Elba Island, located in the Tyrrhenian Sea near the Italian coast, is a small island connected to the mainland by numerous Ro-Ro ferries from the port of Piombino. During the winter, the island has about 31,000 inhabitants, while during the summer months this number significantly increases to over 300,000, making the Piombino-Elba route among the busiest in Italy and the wider Mediterranean area. The ferry journey between Piombino and Elba takes approximately one hour, covering a distance of about 27 kilometers (or 15 nautical miles).

As part of research aimed at modernizing ships to reduce greenhouse gas emissions, the ferry with the smallest capacity from the fleet operating between Piombino and Elba was selected. This ferry is powered by a main engine with a capacity of about 3700 kW and an auxiliary engine of approximately 500 kW, primarily used on the Piombino – Rio Marina route.

The possibility of modernizing Ro-Ro and Ro-Pax ferries is being considered to reduce greenhouse gas emissions in maritime transport, not only while the ships are moored in port but also during navigation. Three modernization scenarios include the complete replacement of main and auxiliary engines with fuel cells, partial replacement of only auxiliary engines with fuel cells, and the use of auxiliary engines equipped with fuel cells exclusively for the needs of the ship while it is in port, on the selected ferry. The required amounts of hydrogen, the time needed for refueling, and the total energy needed for the production, compression, and cooling of hydrogen for each scenario have been analyzed, with the goal of determining the most efficient solution for reducing emissions and increasing the sustainability of maritime transport between Piombino and Elba (11).

Partial modernization of Ro-Pax ferries on the Piombino-Elba route with hydrogen fuel cells for auxiliary systems represents a cost-effective strategy for reducing emissions and energy consumption. This approach allows regular refueling of ferries without significantly extending the ship's port stay time, taking into account the energy and water needs. In light of the challenges associated with complete modernization, partial modernization offers a balanced way to enhance the environmental sustainability of maritime transport while maintaining operational efficiency.

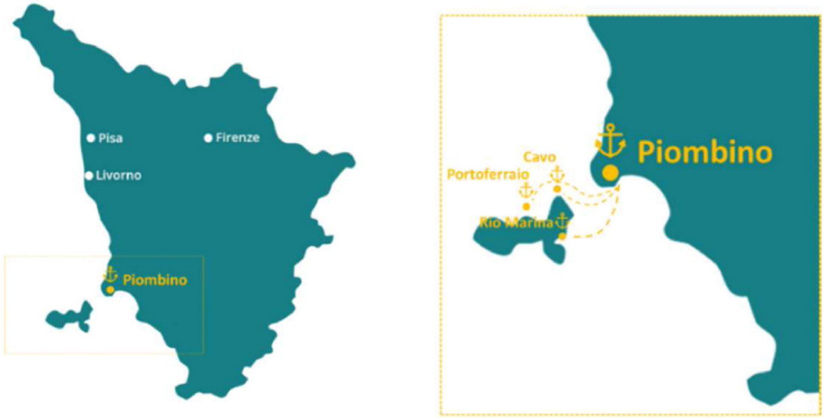

Figure 4. Elba Island and its ports.

5. Conclusion

This paper explores the potential and feasibility of implementing hydrogen-based technologies for the decarbonization of the maritime sector, particularly in the context of coastal transportation on Croatian islands like Vis, Hvar, Korčula, and Lastovo. By analyzing the Vis Solar Power Plant and its potential contribution to green hydrogen production, and considering examples from the Canary Islands and Elba Island, the importance of local renewable sources and innovative energy solutions in achieving sustainable and self-sufficient energy systems is highlighted.

Key findings indicate a high potential for Croatian islands to produce green hydrogen thanks to favorable climatic conditions and the availability of solar energy, making them ideal for the implementation of solar technologies and electrolyzer systems. Examples from the Canary Islands and Elba demonstrate how through international cooperation and financial support, innovative projects that encourage local production and use of green hydrogen can be developed and applied, and how hydrogen technologies can be integrated into existing maritime and energy systems.

The partial modernization of Ro-Pax ferries on the Piombino-Elba route with fuel cells illustrates a practical application of hydrogen technologies in the maritime sector, providing a sustainable solution for reducing greenhouse gas emissions and improving energy efficiency. This approach, combined with the possibility of installing hydrogen refueling stations on islands, paves the way for creating green corridors that would enable sustainable maritime transport based on hydrogen.

In conclusion, this paper highlights the importance of an integrated approach that includes technological innovations, political support, and international cooperation in promoting hydrogen as a key element in the transition towards sustainable and low-carbon energy and transport systems on islands. Considering global decarbonization and sustainable development goals, Croatian islands, along with examples like the Canary Islands and Elba, can serve as models for the application and expansion of hydrogen-based technologies in the maritime sector and beyond.

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