Clean energy for EU islands: Feasibility study on hydrogen ferry service for Isola del Giglio

Clean energy
for EU islands

Feasibility study on hydrogen ferry service for Isola del Giglio

Publication date: 05/07/2024

Authors: BluEnergy Revolution
Reviewers: Martina Cannata (3E), Caterina Carà (POLITO)

Dissemination Level: Public

Published by
Clean energy for EU islands
www.euislands.eu | info@euislands.eu

Table of Contents

List of tables

List of figures

1. Introduction

Maritime transport represents 3 to 4% of the EU's total CO2 emissions, or over 124 million tons of CO2 in 2021 (https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en). In the same year, passenger shipping, which includes cruises and ferries, accounted for a staggering 20 million tonnes of emissions, more than the total national passenger car fleet of the Netherlands. When considering insular territories, transportation to and from the islands accounts for a disproportionately large share of energy usage and, consequently, carbon emissions. This global maritime fuel usage will only increase over time, from a value of 40 Mtoe (tons of oil equivalent) in 2010 to a projected value of 50 Mtoe in 2030, while other sectors (e.g. public road transport, private cars and motorcycles, are reducing their fossil fuels demand (https://clean-energy-islands.ec.europa.eu/system/files/2021-11)

This report is written specifically for the Islands of Giglio and Giannutri, which have requested that the Clean Energy for EU Islands Secretariat study their options for decarbonizing the connection service to and from the islands by introducing hydrogen technology into the ferry vessels. The study considers both the retrofitting of current vessels into hybrid electric-diesel ferries and the introduction of a new FuelCell Electric Ferry fully powered by hydrogen. Different hydrogen supply options to cover the H2ferry service are presented, taking into account safety, logistic, and economic aspects.

This report provides an overview of available technologies based on hydrogen for passengers and RO-PAX ships and then introduces a case study of the islands of Giglio and Giannutri. Based on the analysis of the current service connecting the islands to the mainland, a potential solution to reduce fossil fuel consumption and related emissions is proposed, utilising hydrogen technologies.

1.1. Purpose of the study

This study aims to conduct a preliminary technical and economic assessment of the feasibility of introducing hydrogen-fuelled ferries for passenger and vehicle transportation between the islands of Giglio and Giannutri and the mainland. The technical feasibility study considers both the opportunities of retrofitting existing vessels and introducing new ships' hulls designed for electrical engines and hydrogen fuel cell equipment.
The study should support decisions on investment for the decarbonization of maritime transport in the islands of Giglio and Giannutri, highlighting the costs, barriers, and opportunities offered by hydrogen technologies applied to the maritime sector.

1.2. Methodology

This report presents the work done by the CE4EUI Secretariat, who interacted with the transition team of Giglio and Giannutri with the objective of assessing the possibility of promoting hydrogen in the local short-sea distance ferries operating between the islands and the mainland.
Starting with the presentation of the state-of-the-art hydrogen vessels (CHAPTER 2) and some examples of hydrogen-fuelled and FC-equipped vessels[1], the CE4EUI Secretariat had the chance to collect relevant information about the current ferries service from both the Giglio and Giannutri's Transition Team and public available data in order to propose a step by step process towards

[1] https://www.youtube.com/watch?v=FdlvnpPe8mE&pp=ygUEYmlpbQ%3D%3D

preliminary feasibility for the hydrogen retrofitting of the local fleet (managed by MAREGIGLIO company). This includes:

- Analysis of the sailing route and the fleet operating in the journey (CHAPTER 3), particularly looking at the number of passengers/vehicles mobilised and the frequency of the services (also considering seasonality) in order to understand each trip's fuel consumption and emission production intensity.
- Identification of the most relevant vessel of the fleet to be retrofitted to hydrogen according to its design, its specs (available volume/weight for fuel and propulsion systems) and presentation of a preliminary sizing of fuel cells and hydrogen storage (CHAPTER 4). This sizing has been performed for 100 kg and 400 kg of H2 storage to be integrated onboard following some inputs received by the authors from Isola del Giglio stakeholders.
- Assessment of potential hydrogen supply opportunities, looking at both local hydrogen production potential and hydrogen supplied by an external gas supplier (CHAPTER 4).
- SWOT Analysis related to and comparison of potential retrofitting of existing vessels or building up of a newly crafted Fuel Cell equipped ferry (CHAPTER 5).
- Preliminary Economic (CHAPTER 4) and Environmental Impact (CHAPTER 5) of the proposed case study.

2. Giglio and Giannutri Islands Case Study

Giglio Island is located in the southern part of the Tuscan Archipelago in front of the Argentario promontory. To reach the island, a ferry service is available from Porto Santo Stefano, a town on Monte Argentario on the mainland, which is easily accessible by car, train, or bus. The distance from Rome and Florence is less than 200 km, and it takes approximately two hours to drive.
The embarkations are located directly at the beginning of the town and two shipping companies offer numerous trips throughout the year to Giglio Porto.

Figure 1: Porto Santo Stefano, Isola del Giglio and Giannutri

The Porto Santo Stefano-Giglio ferry route connects the Italian peninsula with Giglio Island by covering a distance of ten nautical miles. Due to the short distance, the ferry journey looks potentially interesting for hybridisation or «hydrogenation» of the local fleet.

Porto Santo Stefano is the largest town on the Argentario promontory and a tourist destination of primary importance for Tuscany, thanks to its magnificent natural context, the beautiful beaches and coves that surround it, but also thanks to its tourist port, always full of yachts from all over the world. Tourists also come to Porto Santo Stefano to embark on the islands of the Tuscan Archipelago, such as the island of Giglio or the small island of Giannutri.

Figure 2: view of Porto Santo Stefano, the port

The island of Giglio is located approximately 15 km west of Monte Argentario, 14 km from the island of Giannutri and 43 km from the island of Montecristo.
The island of Giglio is the second-largest island in the Tuscan Archipelago, after Isola d'Elba. The island's surface measures 21 square kilometres and has a population of around 1,550 inhabitants, distributed among three small, inhabited centres: Giglio Castello, Giglio Porto, and Giglio Campese.
Giglio Castello, the ancient medieval town, home to the Town Hall, is a maze of steep alleys enclosed by walls which culminates with the imposing Rocca Pisana.
Giglio Porto, the island's landing place, is where the last vestiges of the Roman villa belonging to the Enobarbi family are buried under the houses built in the following centuries.
The hamlet of Campese, which faces west onto the largest beach on the island, originates from a mining settlement for the extraction of pyrite, exploited since prehistoric times and closed in 1964.

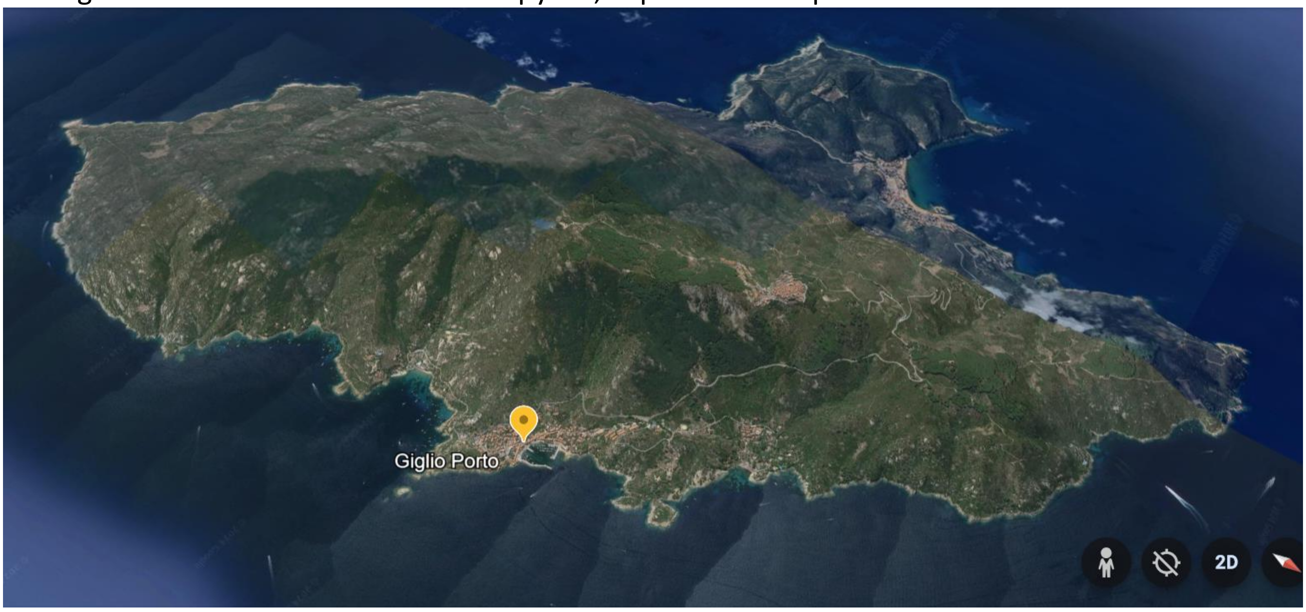


Figure 3: aerial view of Giglio Island, and the port of Giglio Porto

The island’s sea is renowned for its crystal-clear waters teeming with life. Precious meadows of Posidonia Oceanica surround the island, reaching unusual depths, a sign of the clarity and health of the coastline: it is easy to see the now rare seahorse among the leaves. Hundreds of divers explore the waters to enjoy the vertical walls covered with blue sponges and red and yellow gorgonians, around which a life rich in fish and colours develops. In spring and autumn, whales migrate towards the food-rich Ligurian Sea, or dolphins follow the schools of sardines. Giglio Island, in fact, lies within the Cetacean Sanctuary established in 1999, an area of approximately 100,000 km^2 between France, Sardinia, and Tuscany.

Giannutri is part of the Tuscan Archipelago National Park, and for a large part of its surface, it is a protected area. Therefore, it is not allowed to move freely around the island. The access to the island is controlled all year round, and visitors must pay a ticket per each day of stay on the island. Part of the coast is a protected area, and access is prohibited, both by land and by boat.

The coast of the island of Giannutri is also regulated. There is a free zone at Cala Maestra and Cala Spalmatoio, while the rest of the island is subject to severe restrictions and can only be visited using an authorised tour guide.
The island is divided into two zones: Zone 1, also known as Zone A, which is an integral reserve where access, navigation, fishing, and diving are prohibited; and Zone 2, which is an oriented nature reserve. Consequently, fishing is regulated by the Park Authority, and docking of boats is permitted.

Figure 4 Aerial view of Giannutri Island

2.1. Analysis of the route

2.1.1. Porto Santo Stefano -Isola del Giglio:

Giglio Island is well connected to the mainland all year round by two shipping companies, Toremar and Maregiglio.

The Porto Santo Stefano – Isola del Giglio route has its destination at Giglio Porto, the only commercial and leisure port on the island. During the summer season, it is possible to transport private cars to the island, except during the central period of August, when car transport is only allowed for a minimum stay of four nights.

Figure 5: the route Porto Santo Stefano Isola del Giglio

For passengers travelling with no vehicles in Giglio Porto, it is possible to rent scooters or reach the bus stop for Giglio Castello and Giglio Campese

The study of the route considers the present service offered by the two ferry companies for the year 2024. Depending on the season, the ferry service offers from three to seven trips per day, as outlined in the operator's 2024 schedule.

The ferries operating on the Porto Santo Stefano – Isola del Giglio route are active during the summer period, from 07:30 to 19:00, with the last ferry departing from Giglio Porto.
These connections are guaranteed all year round but with some differences regarding departure times.

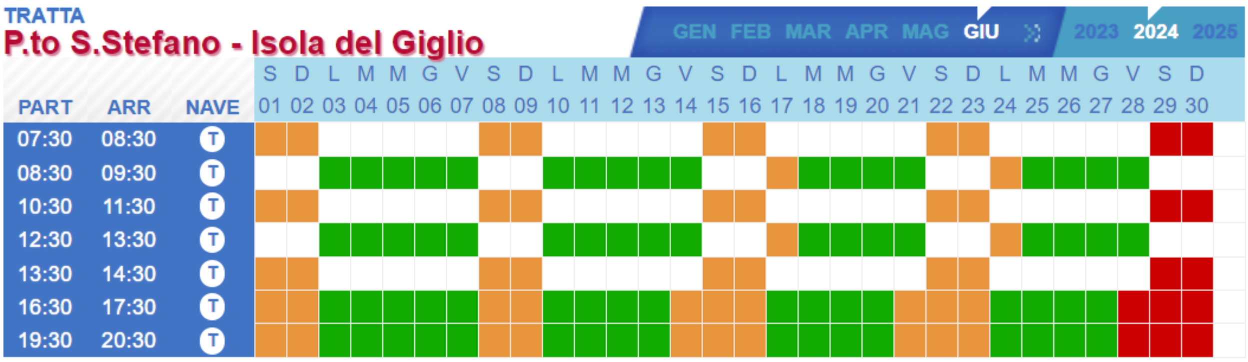


Figure 6: Toremar ferries to Isola del Giglio departures May 2024

Table 1: daily departures Ferry service PortoS. Stefano - Giglio Porto - Giglio Porto- Porto S. Stefano

	MareGiglio - Toremar ferry service Porto Santo Stefano to Isola del Giglio											
	Jan	Feb	Mar	Apr	May	June	July	August	Sep	Oct	Nov	Dec
Trip month	31	28	30	90	93	166	170	170	105	86	30	31
Trip/day	1	1	1	3	3	7	7	7	3	1	1	1

	MareGiglio - Toremar ferry service Isola del Giglio to Porto Santo Stefano											
	Jan	Feb	Mar	Apr	May	June	July	August	Sep	Oct	Nov	Dec
Trip month	31	28	30	90	93	166	170	170	105	86	30	31
Trip/day	1	1	1	3	3	7	7	7	3	1	1	1

The ferry journey from Porto Santo Stefano to Giglio Island lasts, on average, one hour and covers a distance of approximately 22 km, equal to 12 nautical miles.

2.1.2. Porto Santo Stefano -Isola Giannutri:

MV Costa d'Argento operates the Porto Santo Stefano and Giannutri route, providing transport exclusively for passengers with a maximum capacity of 350 people. On the island of Giannutri, the transport of vehicles is not permitted except for residents or work reasons.
The frequency of the service all year around is one trip a day; from November to March, the service operates on Wednesday and Saturday with one departure a day, while in the high season, the connection with Giannutri operates up to 5 days a week (Monday, Wednesday, Friday, Saturday, and Sunday)

Table 2: daily departures Ferry service PortoS. Stefano - Isola Giannutri - Isla Giannutri- Porto S. Stefano

	MareGiglio - Toremar ferry service Porto S.Stefano to Isola Giannutri - Isola Giannutri PortoS.Stefano											
	Jan	Feb	Mar	Apr	May	June	July	August	Sep	Oct	Nov	Dec
Trip month	10	8	16	16	16	20	20	20	20	16	30	31
Trip/week	2	2	4	4	4	5	5	5	5	4	2	2

2.2. Analysis of the fleet and identification of the case study

The Porto Santo Stefano – Giglio Island route is operated by two RO-PAX ferries:

- M/V Isola del Giglio, which can carry up to 595 passengers and 40 vehicles
- M/V Dianium, which can carry up to 345 passengers and approximately 12 vehicles

Maregiglio fleet operates two additional ferries supporting Isola del Giglio and Dianium ships during the peak season:

- M/V Revenge, only passengers up to 399 seats
- M/V Costa d'Argento, only passengers up to 390 seats

Revenge and Costa d'Argento are the most recent units and operate also for charter services.

Toremar company operates the motor vessel Giuseppe Rum, a RO-PAX vessel with a capacity for 633 passengers and 40 vehicles.

Of the five vessels in service, only Dianium and Isola del Giglio operate exclusively on the Porto Santo Stefano-Giglio Porto route.

The numbers presented show that the local fleet (with vessels equipped with engines with less than 1 MW of power capacity) could have some chances to be converted to H2, but such fleet decarbonisation should be accompanied by a proper H2 Infrastructure development in both the island and the mainland.

2.2.1. M/V Isola del Giglio

M/V Isola Del Giglio		
Length	m	62
tonnage	tons	749
Engine	MW	2 x 2.0
Capacity	pax	595
	vehicles imp	40

The M/V Isola del Giglio is the flagship of the fleet; it was launched in 1972 in Norway under the name Stavanger and has been serving the Porto Santo Stefano-Isola del Giglio route since 2000.

In 2020, it underwent major maintenance work, which equipped it with the most modern navigation equipment and new, low-powered engines that combine greater energy efficiency with a lower environmental impact. The ship offers a bar service inside the spacious salon on the first deck and two large outdoor areas on the first and second decks, ideal for making the most of the voyage on fine summer days.

With a Nordic tradition and designed for the northern seas, the Motorship Isola del Giglio is known for its excellent seaworthiness even in unfavourable sea weather conditions.

Figure 7: M/V Isola del Giglio, Source https://maregiglio.it/la-flotta/mn-isola-del-giglio/

2.2.2. M/V Dianium

M/V Dianium		
Length	m	42,5
tonnage	tons	198,6
Engine	MW	2 x 0.716
Capacity	pax	345
	vehicle	12

The M/V Dianium is the historic ferry of the Maregiglio company, which has been active on the Porto Santo Stefano - Isola del Giglio route since 1989, the year of its construction.

The RO-PAX ferry was commissioned by the Maregiglio Company to the Cantieri Uniti of Viareggio and can carry passengers and vehicles.

It features a double lounge on both the first and second decks, as well as an outdoor area.

Figure 8: M/V Dianium Maregiglio, Source https://maregiglio.it/la-flotta/dianium/

2.2.3. M/V Revenge

The Revenge is considered the most elegant vessel in the fleet of Maregiglio's Company. Used for passenger transport only, the vessel is designed with modular lounges, and furnishings and it is available during the year for Mini Cruises and private events.

The M/V Revenge was the first eco-labelled ship in Europe in its category with RINA "Green Star" certification.

M/V Revenge		
Length	m	39,7
tonnage	tons	93,55
Engine	MW	2 x 1.25
Capacity	pax	399
	vehicle	NA

Figure 9: M/V Revenge Source: https://maregiglio.it/la-flotta/revenge

2.2.4. M/V Costa d'Argento

The M/V Costa d'Argento is the most recent vessel joining the Maregiglio fleet. The vessel is mainly used to cover the route Porto Santo Stefano – Giannutri, but it seldom services also the route to Giglio Island.

The vessel is arranged on three decks and features two French-made Boduin engines, each with a power output of 1,500 hp.

M/V Costa d'Argento		
Length	m	34,37
tonnage	tons	84,55
Engine	MW	2 x 1.5
Capacity	pax	390
	vehicl	NA

The vessel has a Fiberglass hull built by the Agostini Shipyard of San Zaccaria in Ravenna, then built and fitted out by the Boschetti Shipyards. It is equipped with all comforts, the latest generation safety systems, is particularly quiet during navigation, and has extremely low consumption.

Figure 10: M/V Costa D'Argento Source: https://www.vesselfinder.com/it/ship-photos/867933

2.2.1. M/V Giuseppe Rum

The M/V Giuseppe Rum is a ferry owned by the Italian shipping company Maregiglio, currently in service on behalf of Toremar, servicing the route Porto Santo Stefano Isola del Giglio. The vessel was built specifically for the Porto Santo Stefano-Isola del Giglio route, has only essential services such as a bar, lounge and solarium on the external deck. The ferry can carry up to 40 accompanying cars for a capacity of 623 passengers.

M/V Giuseppe Rum		
Length	m	51
tonnage	tons	700
Engine	MW	2 x 1.49
Capacity	pax	623
	vehicle	40

Figure 11: M/V Giuseppe Rum
Source: https://commons.wikimedia.org/wiki/File:Giuseppe_Rum_Porto_Santo_Stefano.jpg

3. Case study Assessment

Building on the information related to the operating fleet and the sailing journey presented in Chapter 3, this paragraph examines the possibility of integrating a newly crafted full hydrogen ferry into the MAREGIGLIO fleet, as per the information on the ferry service connecting Porto Santo Stefano and Giglio Porto. Such a new zero-emission ferry should be used throughout the year (indicatively to cover the number of services currently provided by M/V Isola del Giglio).

Considering that M/V Isola del Giglio (770 sailing services out of the yearly 1030 services) and M/V Dianium (297 sailing services out of the yearly 1030 services) are exclusively used for this route, their consumption, engine power capacity, fuel tank sizes and passengers' capacity are used as reference.

Table 3: *Shared information about the Maregiglio fleet*

	Length	tonnage	Engine	Capacity		Fuel Consumption		Trip	Avg Power used
	m	tons	MW	pax	vehicl	kg/trip	kg/year	/year	kW
Isola Del Giglio	62	749	2 x 2.0	595	40	460	356000	773,9	828
Dianium	42,5	198,6	2 x 0.716	345	12	400	119000	297,5	720
Revenge	39,7	93,55	2 x 1.25	399	NA	550	90000	163,6	990
Costa D'argento	34,37	84,55	2 x 1.5	390	NA	500	62000	124,0	900
G.Rum	51	700	2 x 1.49	623	40	600	789000	1315,0	1080

Firstly, a potential sizing of the FC System and H2 storage to be installed on board the ferry is defined: the amount of hydrogen required by the new H2 ferry to cover the mainland-island connection is assessed based on the power of the FC engine and the distance to cover the route. Then, the amount of green hydrogen that can be produced onsite is estimated to benchmark it with the total quantity needed to satisfy the ferry service all year round. The assessment explores possible options based on varying levels of service coverage with the new hydrogen vessel, considering the available spaces for a hydrogen refuelling station in the Porto Santo Stefano port area and the logistics for potential H2 supply and storage.

Finally, an operating model of the H2 ferry service for Porto Santo Stefano Isola del Giglio connection is presented, highlighting CAPEX for the vessel and the hydrogen infrastructure required to manage the storage of hydrogen, the refuelling operations, the supply of hydrogen from external suppliers, and the regulations and safety aspects to meet for the licensing of the system.

3.1. Fuels cell power capacity onboard

According to the values presented in the table above, it is reasonable to foresee a propulsion system on board having a potential Fuel Cell System of 800 kW, with a redundancy diesel engine, also to facilitate the fulfilment of vessel regulatory aspects, which require bringing on board not only the fuel for the regular operation of the vessel but also for its emergency (thus posing weight/volume challenges for a second FC/H2 storage on board allocation). Thus, a further 800 kW Diesel Engine and a fuel tank of 200 l (enough to cover at least one trip) are considered for installation on board the new hydrogen vessel as an emergency or redundancy engine (a 1000 l tank is considered for simplicity and safety).

The proposed propulsion system setup is presented in Figure below. It foresees a PEMFC as the primary power generation source, supplying the required propulsion power for all operational modes, with the support of a battery rack for hotel loads in port and operational modes, as well as to manage severe load transfer, thereby avoiding the need for strong current fluctuations in the FC.

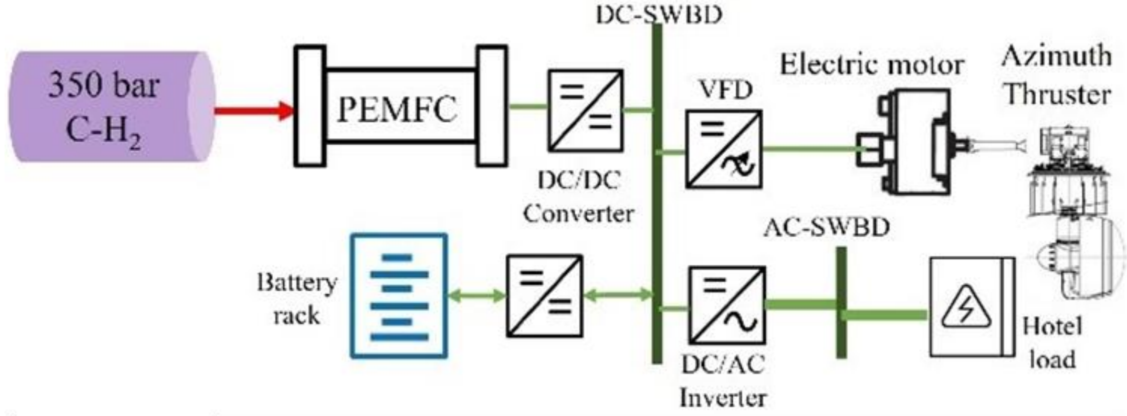
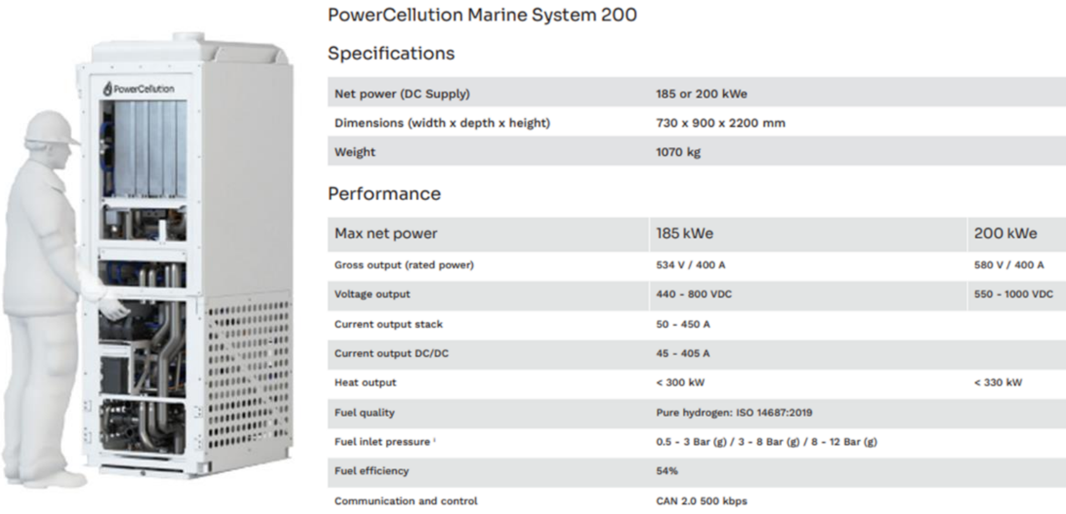


Figure 12: *Proposed propulsion system*

Looking at on-the-market solutions and to exploit the FCs at their maximum efficiency (thus reducing the amount of hydrogen on board), 5x200 kW FC modules are considered to be installed on board the vessel instead of 4x200 kW: this has, of course, an impact on the CAPEX, but it enables (as operating at higher efficiency) to reduce the volume and weight of hydrogen to be installed on board. Looking at marinised FC systems (thus having received a preliminary type of approval from a classification society) available on the market, like from BALLARD (Fig.36) or PowerCell (Fig.37) that can be considered, the overall weight and volume for the FC system to be integrated on board in the technical machine area is foreseen (Table 12).

Performance	
Rated power	200kW
Minimum power	55kW
Peak fuel Efficiency	53.5%
Operating voltage	350 - 720 V DC
Rated current [1]	2 x 300 A 1 x 550 A
System cooling output	Max 65° C
Stack technology	
Heat management	Liquid cooled
H2 Pressure	3.5 - 6.5 Barg
Physical	
Dimensions (l x w x h) [2]	1209 mm x 741 mm x 2195 mm
Weight (estimate) [3]	1000 kg
Environmental protection	IP44
Engine room (DNV GL CG-0339)	+0°C - +45°C
Minimum start-up temperature	0°C
Short-term storage temp	-40°C - +60°C
Reactants and Coolant	
Type	Gaseous hydrogen
Composition	As per SAE spec. J2719 and ISO 14687:2019 Type I, Type II - Grade D
Oxidant	Air
Composition	Particulate, Chemical and Salt filtered
Coolant [4]	Water or 50/50 glycol
Safety Compliance	
Certifications [5]	DNV-Type Approval
Enclosure	Sealed secondary barrier for hydrogen

Figure 13: *Ballard Marinized PEMFC systems – 200 kW – technical specs*



PowerCellution Marine System 200

Specifications

Net power (DC Supply)	185 or 200 kWe
Dimensions (width x depth x height)	730 x 900 x 2200 mm
Weight	1070 kg

Performance

Max net power	185 kWe	200 kWe
Gross output (rated power)	534 V / 400 A	580 V / 400 A
Voltage output	440 - 800 VDC	550 - 1000 VDC
Current output stack	50 - 450 A	
Current output DC/DC	45 - 405 A	
Heat output	< 300 kW	< 330 kW
Fuel quality	Pure hydrogen: ISO 14687:2019	
Fuel inlet pressure [1]	0.5 - 3 Bar (g) / 3 - 8 Bar (g) / 8 - 12 Bar (g)	
Fuel efficiency	54%	
Communication and control	CAN 2.0 500 kbps	

Figure 14: *PowerCell Marinized PEMFC systems – 200 kW – technical specs*

Table 4: *Overall weight and volume for the proposed setup*

Parametro	**Ballard FC Wave**	**PowerCellution Marine System**
Power Capacity [kW]	200	200
Minimum Power [kW]	55	N/A
Efficiency	53,5%	54%
Weight [kg]	5x1000 = 5 t	5x1070= 5,35 t
Sizes [m]	1,21 x 0,74 x 2,2	0,73 x 0,9 x 2,2
Volume [m^3]	5x1,97 = 9,85 m^3	5x1,45 = 7,25 m^3

Due to higher compactness and efficiency, the PowerCell Solution has been considered for the next steps.

3.2. Hydrogen Storage capacity onboard

Looking at hydrogen storage, an overall amount of 80-100 kg of H2 should be considered to be stored on board. Such value has been estimated based on the overall fuel consumption per trip (approximately 700 kWhEP, equivalent to around 40 kg of H2) and fuel cell operability (with an average fuel cell efficiency of 55%) along a journey of approximately 12 Nm. Such value can also be somewhat validated by the overall yearly diesel engine consumption of the M/V Isola del Giglio and M/V Dianium vessels.

Most probably, the refuelling will occur on the mainland in a hydrogen refuelling station in Porto Santo Stefano. The onboard hydrogen storage is sized at 100 kg, foreseeing an H_2 storage refuelling

every round trip (looking at the ferry schedule, this possibility looks feasible even considering the time needed for hydrogen bunkering and refuelling).
The possibility of storing H2 on board via 350 bar compressed hydrogen storage bottles is foreseen. Looking at commercially available solutions (Table 13), the highlighted bottles are the best option for targeting a relevant weight ratio. Therefore, the installation of 10 bundles, with an overall weight of 1340 kg for the hydrogen bottles and approximately 300 kg for hydrogen management devices (valves, instrumentation), is considered.

Table 5: *350 bar H2 bottles specs*

	Nominal working pressure (15°C)	Outside diameter	Overall length	Cylinder weight	Water volume	Hydrogen capacity	Weight ratio (hydrogen weight/cylinder weight)
Reference	Bar	mm	mm	kg	L	kg	%
H2-35-430X3190	350	430	3,190	101	312	7.5	7.4
H2-35-430X2110	350	430	2,110	67	193	4.7	7.0
H2-35-450X3283	350	450	3,190	109	362	8.8	8.1
H2-35-450X2158	350	450	2,110	71	225	5.4	7.6
H2-35-450X3600	350	450	3,600	124	416	10.1	8.1
H2-35-509X2342	350	509	2,324	112	350	8.4	7.5
H2-35-509X2029	350	509	2,029	95	300	7.2	7.6
H2-70-530X2154	700	530	2,154	188	244	9.8	5.2
H2-70-600X2060	700	600	2,060	191	364	14.6	7.6
H2-70-705X2078	700	705	2,078	272	457	18.4	6.8

The volume of the H2 storage system (also considering hydrogen management devices to be foreseen) is approximately 5.5 m³. This value (also considering that we're referring to 10 x 3,6 m long bundles) poses some challenges in identifying an external location for the hydrogen storage on the available docks of the M/V Isola del Giglio or the M/V Dianium without issues of payload (passengers/vehicles reduction): for this reason, the choice of a new zero-emission vessel seems to be the more appropriate.

To ensure the safety of passengers and avoid complex safety distance allowances on board, as previously implemented in various H2 Ferries experiences (e.g., Fig. 6-7), an elevated deck dedicated solely to hydrogen storage is recommended. This elevated deck is not present in M/V Dianium while it is present in M/V Isola del Giglio; however, in the second case, it is currently hosting passengers/owners of cars stored in the lower deck, while a "full elevated deck for H2" should be considered, with the only further eventual presence of the pilot cabin (as reported in Figures below).

Figure 15: *Example of elevated deck dedicated to CH2 Storage*

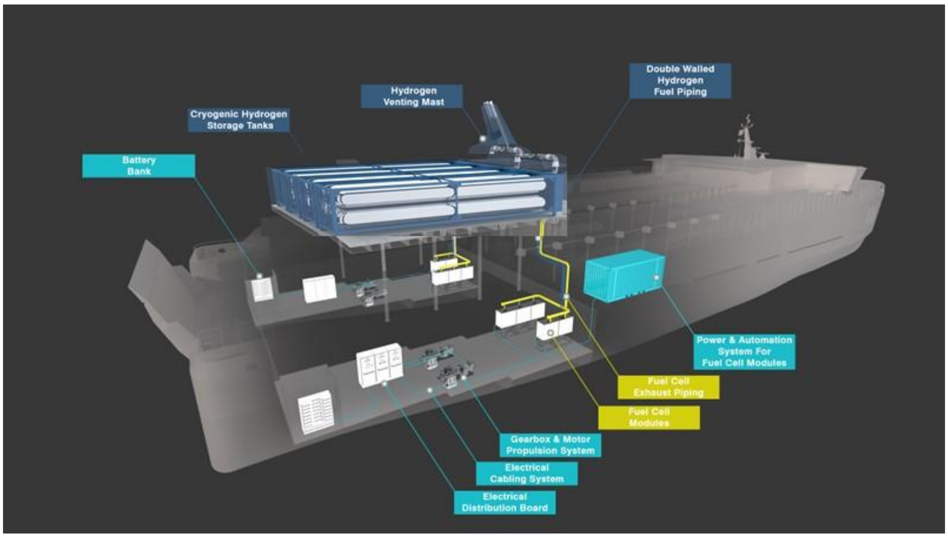


Figure 16: *Potential layout of the hydrogen ferry with dedicated CH2 Storage deck*

The choice of an elevated "dedicated" deck is also suggested to facilitate the refuelling procedures of the hydrogen storage system.

For 350 bar, the average refuelling rate of a hydrogen bottle with the size that is suggested above is indeed around 1.5 kg/min[2], thus foreseeing for the above-described ferry a refuelling time of around 75-90 min (considering also the plugging/unplugging procedures of the bunkering, the arrival on the deck of the hydrogen truck etc.): this timing could be complicated to be managed in small and crowded ports like Porto Santo Stefano or Isola del Giglio. Thus, an "empty-full" swapping of a container/bundle can be a faster operation (and potentially to be realised from a barge on the sea, too – maximum time 30 minutes).

Summarising volumes and weight of the new system: the power converters need the overall weight and volume of the integrated FC/Hydrogen powertrain equivalent to a volume of 14,5 m^3 (of which 12,75 m^3 dedicated to a 100 kg compressed H_2 storage and fuel cell system) and to a weight of 7,8 t (of which 7 t to H2 storage and fuel cell system), and in addition to this the contribution of the volume and weight of the redundant diesel system with a 400-460 kg of fuel tank (equivalent to 100 kg H2 storage), to provide a round trip of the vessel in case of failure of the H_2 system.

3.3. Hydrogen demand for the case study

In this paragraph, the amount of hydrogen needed to cover the ferry service between Porto Santo Stefano and Giglio Porto is presented. It is assumed that a new hydrogen vessel will operate the route with priority, covering all services during the low season (October-April, see Paragraph 3) and up to three round trips per day between Porto Santo Stefano and Giglio Porto. The frequency of departures for the H2 ferry from Porto Santo Stefano will be at least four hours.

---

[2] Roberta Caponi, Andrea Monforti Ferrario, Luca Del Zotto, Enrico Bocci, Hydrogen refuelling stations and fuel cell buses four year operational analysis under real-world conditions, International Journal of Hydrogen Energy, Volume 48, Issue 54, 2023, Pages 20957-20970, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2022.10.093

The vessel can run a roundtrip journey consuming 80 kg of hydrogen and will have a reservoir of 100 kg of hydrogen (as reported in the previous paragraphs).

H2 FERRY 1MW single route performance		
distance	12.0	mil
duration	60	min
Speed	12.0	kn
kWh	690.00	kWh
H2 consumption	38.0	kg

Table 6: Number of roundtrips for the 2024 year timetable of Maregiglio/Toremar

	Hydrogen deamnd and ferry servicecoverage Porto Santo Stefano to Isola del Giglio												
	Jan	Feb	Mar	Apr	May	June	July	August	Sep	Oct	Nov	Dec	TOTAL
RoundTrip month	26	24	25	90	93	166	171	175	105	26	26	26	953
RoundTrip/day	1	1	1	3	3	7	7	7	3	1	1	1	na
H2 Trip/month	26	24	25	90	93	90	93	93	87	26	26	26	699
H2 /day [kg]]	80	80	80	240	240	240	240	240	240	80	80	80	na
H2/month [kg]	2080	1920	2000	7200	7440	7200	7440	7440	7200	2080	2080	2080	56160
H2 Ferry %	100.0%	100.0%	100.0%	100.0%	100.0%	54.2%	54.4%	53.1%	82.9%	100.0%	100.0%	100.0%	73.3%

According to the timetable for 2024 (https://maregiglio.it/orari), during the low season, the ferry operates one round trip a day from Monday to Saturday (November and December). In the mid-season, the number of trips increases to three roundtrips a day, seven days a week. In the high season, the number of roundtrips per day is five on Monday through Friday and seven on Saturday through Sunday.

On the route between Porto Santo Stefano and Isola del Giglio, the possible hydrogen ferry can reduce emissions by more than 70% annually, operating up to 700 trips, which is the total number operated by Maregiglio-Toremar for the year 2024.
The supply chain of the hydrogen to the ferry HRS should be able to balance the fluctuation of the demand that ranges from 80-100 kg per day during the low season (1 round trip per day) and goes up to 240-300 kg a day in the mid (3 round trips per day) and high (in which the H2 ferry operate half of the round trips) season.
Seasonality ideally follows the pattern of PV generation, with a peak in production during summer and lower production during winter, making it reasonable to evaluate the possibility of self-producing hydrogen for use on board.

3.3.1. PV Plant Coupled to a PEM Water Electrolyser

A PV plant is considered to be coupled with a hybrid battery-electrolyser hydrogen production facility to produce green hydrogen, satisfying the H2 ferry needs.
The plant can be sized based on the hydrogen requirements of a 240 kg/day production scenario, which would require a renewable green power generator of approximately 3 MWp to produce an average of about 200 kg H_2/day.
A 3 MWp renewable PV generator, based on the site's latitude near the Italian coasts, can provide between 1,200 and 1,400 equivalent hours (approximately 3.8 hours of operation per day) of

electricity production per year at its rated installed peak power (MWp). Such a 3 MWp renewable PV system would be able to produce an average of 11,400 kWh/day of electric energy, resulting in a production of approximately 200 kg H2/day via an electrolyser with an efficiency of 55 kWh/kg H2 (60% HHV).

Figure 17. PV generator on carport in a carpark

A PV generator is an ideal renewable generator for hydrogen production in regions with good solar irradiation, such as the Italian coasts, although the power output depends on availability and quantity from seasons and weather conditions.

The average value of solar irradiance on a yearly base is quite reliable, but the production hours are limited to the daytime period all throughout the year; moreover, bad weather and clouds can significantly cut production unexpectedly. Also, from a technical point of view, the possible fluctuation of power of the PV generator is not ideal for the performance of the PEM electrolyser, which conversion efficiency drops in the transients.

Considering the above-mentioned limitations of the PV solar technology and electrolyser-specific requirements, the sizing of a hydrogen production facility based on the hybrid battery-electrolyser concept elaborated by Bluenergy Revolution is presented.

3.3.2. Hybrid Energy Storage

To match the PV peak power, the electrolyser should be sized for a maximum output power of nearly 3 MW. The alternate use of the electrolyser, with daily startups and shutdowns, is not an ideal condition for the system.

For these reasons, a hybrid system composed of an electrolyser and batteries is proposed, and the size and control method is based on two types of energy storage better to manage the PV power output and the hydrogen production.

- The electricity storage can collect the excess production from the PV generator during the daytime and give it back to the electrolyser after sunset, thus extending the daily operating hours of the electrolyser. The size of this storage is proportional to the daily energy produced by the PV plant.
- The hydrogen storage collects the hydrogen produced by the electrolyser until there is a request from the dispenser of the HRS or from the empty tanks on a trailer. The size of the hydrogen storage is dependent on the hydrogen application.

A large battery storage system negatively impacts the initial investment costs, but it enables the downsize of a more expensive part of the plant, the electrolyser, which could be at a power ratio of 1:4 with respect to the peak power of the PV generator. Moreover, the high flexibility of the system would enable hydrogen production optimisation according to specific targets and better PV energy exploitation.

3.3.3. Simulation of Green Hydrogen Production

The electrolyser modelled in the system is based on PEM technology and has been sized in accordance with the hybrid solution presented before against the maximum allowed PV power of 3 MWp, resulting in an electrolyser maximum power of 1000 kWp, able to produce up to 16 kg/hrs of green hydrogen. According to the previous paragraph, this technology provides hydrogen with a pressure of about 30 bar at the outlet.

The electrolyser is controlled within the system by a specific logic that optimizes system performance and maximises hydrogen production. As an example, the control stops the electrolyser at a defined state of the hydrogen storage or the battery and the PV power output to avoid power shortage on the electrolyser and prevent prompt deterioration of the membrane and Balance of Plant (BoP).

The following, it is shown the performance in terms of hydrogen production that is achievable when such a hydrogen production system is powered by a 3 MWp PV generator on the coasts of Italy.

The proposed hydrogen generator system has been designed to achieve maximum annual production of green hydrogen, with the control logic and component design optimised to meet this target, utilising only renewable energy sources (RES) in an off-grid configuration.

Results of possible performance are presented in relation to the average potential production of a PV generator operating in Italy at the latitude of the Tuscany region. For this region, an average value of 1400 kWh/kWp is considered as a reference for the yearly energy production of the PV generator. The performance of the system is presented for three levels of production potential/hydrogen demand:

- Summer (May – September);
- Spring/Autumn (September –November, and March-May);
- Winter (November –March).

The level of production varies according to the seasonal level of solar irradiation. However, the demand for hydrogen is also expected to follow seasonal trends, with higher demand during the

summer season and a decrease during winter. The size of the designed system allows the operation of the electrolyser to exploit up to 90% of the 1 MWp PV generator energy production.
According to the selected control strategy, which aims to maximise the yearly hydrogen production, it is possible to manage the electrolyser to work at its nominal efficiency for over 6000 hrs a year, although the winter season presents few days of very low solar irradiation that prevents the reach of the minimum power to start the electrolyser.
The following presents a summary of the design process carried out using a dedicated tool. The sizing and optimisation tool used by Bluenergy Revolution is not only used to size the system components but also to develop specific management strategies for the overall power-to-hydrogen plant.
In the following graph, a typical winter scenario is depicted, featuring 2 days of solar irradiance per week. In this example, the behaviour of a system without considering the starts and stops of the electrolyser is reported, highlighting the difficulty of managing reliable simulations and sizing the system.

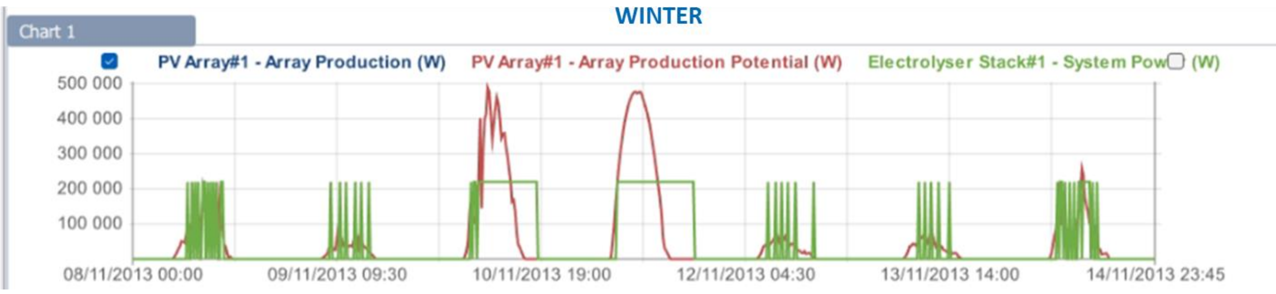


Figure 18: Electrolyzer control strategy based on Electrical storage state of charge

This presented model aims to assess the ability to operate an electrolyser powered exclusively by a PV generator, and it does not consider the option to get power from the electrical grid, so a few hours of the stop of the electrolyser in the winter season have to be taken in to account. The sudden lack of power, in any case, is managed by the system to ensure the proper working conditions of the electrolyser, with a check on the state of the PV generator and the state of charge of the electrical storage.
With an optimised control strategy, it is possible to convert into hydrogen the largest part of the available PV energy, modulating the electrolyser power while exploiting the battery storage. This could result in a weekly production of over 300 kg, even during the winter season.
The hybrid system enables the optimised management of intermediate situations, giving the possibility to operate the electrolyser at its maximum efficiency point as much as possible. The importance of simulations for such systems extends beyond the control strategy to include system sizing.
The energy made available from the PV generator in the summer season presents peak and average values much higher, so it would be possible in the summer to operate a larger electrolyser, and a different balance of the system can be chosen to foster larger hydrogen production in summer, increasing the size of the electrolyser, and therefore the capex but also the seasonal production.

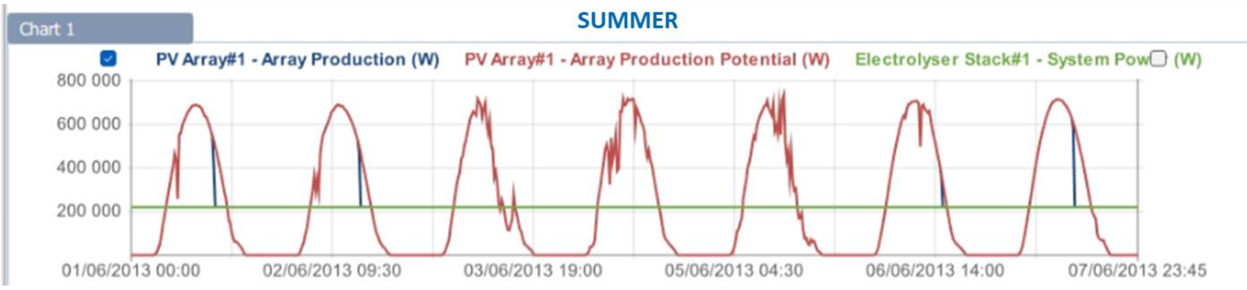


Figure 19. Summer hydrogen production, the electrolyser operates 24 h a day, PV daily generation exceeds daily electrolyser maximum capacity

The quantity of hydrogen that can be produced by a 3MWp PV generator and a hybrid green hydrogen generator in Italy is presented with daily, weekly, and monthly details.
If we examine the data on the potential production of hydrogen by a 3MWp PV system on a daily basis, we can observe a significant variation between the seasons, specifically Summer and Winter. In fact, the variation in daily potential production on a weekly basis goes over 600% (i.e. Dec W1 Vs June W1), with average daily values of 45 kg/day in winter and a peak of 270 kg/day in the summer.

An estimation of the hydrogen production from a 3 MWp PV generator and BESS operating in Italy is shown in Table 15 below.

Table 7: Estimated hydrogen production based on 3 MWp PV generator, operating at 1400 equivalent hours/year

	DAILY H2 POTENTIAL PRODUCTION FROM 3 MWp PV GENERATOR IN mid ITALY												
	Jan	Feb	March	April	May	June	July	August	Sept	Oct	Nov	Dec	
	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	
W1	109.2	145.2	169.8	243	237.9	263.7	261.9	262.2	221.1	176.7	169.2	50.1	
W2	154.8	145.8	230.1	175.8	256.8	263.1	262.8	245.7	200.1	174.3	65.1	144.3	
W3	96.9	142.8	221.7	218.1	259.2	258	261	211.8	256.8	109.2	99	93	
W4	169.2	127.2	227.7	231.9	219	263.1	257.1	252	164.7	157.8	57.3	110.1	**Kg/y**
TOTAL	4 111	3 931	6 584	6 516	7 542	7 857	8 082	7 533	6 318	4 790	2 934	3 078	**69 276**

3.4. H2 onsite production and storage

Starting from the results of §3.2, in this paragraph, a technical solution to provide the amount of hydrogen useful to satisfy the hydrogen demand of the ferry service to Isola del Giglio is presented.
An integrated system (to be potentially installed in Porto Santo Stefano) with an electrolyser, hydrogen storage and dispenser for refuelling the vessel reservoir is presented. As presented in Chapter 2, hydrogen production and storage technologies are mature, and the market offers alternative solutions with specific features.
The ferry refuelling infrastructure can integrate a hydrogen production unit and hydrogen storage. The electrolyser, the component that converts electricity into hydrogen molecules through water splitting, will be powered by renewable energy produced from the RES generator or via a PPA (Power Purchase Agreement), enabling the direct purchase of renewable energy from the grid.
This integrated H2 production – storage – refuelling system could have an architecture similar to the one realised in Antwerp by CMB.TECH[3] , but targeting the respect of the Italian regulatory framework

[3] https://www.youtube.com/watch?v=EPnT8kRYNWI

for HRS (DM 23 October 2018) and its safety distances (which are usually quite challenging, obliging >15 m of empty space around the HRS point).
In the next paragraphs some preliminary information is shared.,

3.4.1. Electrolyser Unit: Proton exchange membrane (PEM)

A suitable electrolyser technology for the case is a Proton Exchange Membrane: PEM Electrolysers are currently considered the best compromise between innovation and state-of-the-art modern electrolysis systems. Products on the market, such as NEL MC electrolysers, come in a containerised form facilitating installations, manufacturers offer turnkey solution contracts, and the products are reliable and can be operated with minimal maintenance.

SPECIFICATIONS		MC250
Net Production Rate		246 Nm^3/h 531 kg/24 h
Production Capacity Dynamic Range		10 to 100%
Power Consumption at Stack at 100% Capacity[1]		4.5 kWh/Nm^3 53.2 kWh/kg
Power Consumption by System at 100% Capacity[1]		5.2 kWh/Nm^3 58.3 kWh/kg
Purity (concentration of impurities)		99.95% [H_2O < 500 ppm, N_2 < 2 ppm, O_2 < 1 ppm, all others undetectable]
Purity (concentration of impurities with optional high purity dryer)		99.9995% [H_2O < 5 ppm, N_2 < 2 ppm, O_2 < 1 ppm, all others undetectable]
Delivery Pressure		30 barg (435 psig)
Dimensions W x D X H	Electrolyser Enclosure[2] Power Supply Enclosure	12.2 m x 2.5 m x 3 m (40 ft x 8 ft x 9.9 ft) 6.1 m x 2.5 m x 2.6 m (20 ft x 8 ft x 8.5 ft)
Ambient Temperature[3]		-20 to 40ºC (-4 to 104ºF)
Electrolyte		Proton Exchange Membrane
Potable Water Consumption[4]		1.5 l/Nm^3 (0.4 gal/Nm^3) of H_2 15.9 l/kg of H_2 (4.2 gal/kg of H_2

Figure 20: 1MWp PEM electrolysis specification

3.4.2. Hydrogen storage system

Two different hydrogen storage solutions have been considered: compressed hydrogen storage and metal hydride.
To evaluate the compressed hydrogen storage specs, bundles presented in §3.1 can be considered targeting a local stationary storage of around 400 kg to be integrated into a bunker, while for what concerns Metal Hydrides, the possibility to store them via racks or containers like those realised by METHYDOR[4] could be foreseen (considering a volume occupancy around 40 m^3 and total weight – not an issue for stationary application – of 44 t)

[4] https://methydor.com/

3.5. Hydrogen refuelling station (HRS) for Isola del Giglio ferry service

The refuelling process in a hydrogen station is not much different from that of a conventional petrol station, although hydrogen is supplied at high pressure. Thus, hydrogen refuelling stations differ from traditional liquid fuel stations by the level of control required during fuelling to maintain safety.
While liquid fuel is delivered just above ambient pressure by forcing fuel through the pressure losses of the dispenser, delivering hydrogen means manipulating gas at up to 900 bar, creating large mechanical and thermal stress within vehicle tanks. Besides, to remain competitive with conventional fuels, a similar refuelling time of 3-4 min is expected (in the case of storage of H2 at 700 bar, currently used only on buses and trucks and with an H_2 refuelling rate of around 5-7 kg/min depending on the capability of the dispenser to be cooled down), which further amplifies stress due to the quick dynamics of constraint build-up.
Currently, 350 bar HRS operates with an H_2 refuelling rate of around 1,5 kg/min. Thus, a potential "empty-full" swapping approach of the bundles to be moved on the H2Storage deck is suggested (as currently done in different H2 vessels in Europe).

3.5.1. Hydrogen bunkering safety

Recalling the IMO target for the 50% reduction of greenhouse gases related to the maritime sector by 2035, hydrogen is entitled to be the dominant energy carrier for the future. However, it is not straightforward to replace conventional fuels with hydrogen, as the safety-related properties of hydrogen require alternative considerations and solutions. Compared to conventional fuels used in the maritime sector, hydrogen mixtures with air have a significantly wider flammable range, a very low minimum ignition energy and are significantly more reactive.
In such respect, the IGF Code requires that "… *The safety, reliability and dependability of the system shall be equivalent to that achieved with new and conventional oil-fuelled main and auxiliary machineries…*".
The possibility of operating with a potential "empty-full" swapping approach for the bundles to be moved on the H2Storage deck is also suggested for bunkering regulation and safety prescription aspects (as currently done in different H2 vessels in Europe).

3.6. Hydrogen supply chain for Isola del Giglio hydrogen ferry service

As mentioned, refuelling operations should most probably occur at the Porto Santo Stefano port on the mainland; the HRS will be able to produce its own hydrogen thanks to an electrolyser unit powered by renewable energy (PV + PPA).
The size of the hydrogen production and storage for the HRS design is based on the results of four possible supply scenarios:

a. ***Hydrogen demand satisfied by a local PV Plant***: considering the CAPEX of the PV plant and its operativity, the levelized cost of self-produced hydrogen could be around 6÷8 €/kg
b. Hydrogen demand satisfied by a PPA with electricity purchased from the grid: considering a PPA of around 70 €/MWh, the levelized cost of self-produced hydrogen could be around 6÷8 €/kg

c. ***Hydrogen demand satisfied by a hybrid system*** (thus foreseeing potentially a smaller PV plant and therefore reduced CAPEX, but with OPEX related to electricity purchase via a PPA in case of need of power not to be provided by the PV plant)
d. ***Hydrogen delivered by a gas supplier:*** considering that the PEM Fuel Cell to be installed on board the ferry would require high purity hydrogen (5.0) at quite high cost of delivery (nowadays around 20-30 €/kg depending on the daily required amount) this option seems not to be the most preferable.

Depending on the refuelling technology, hydrogen can be delivered to the HRS in either gaseous or liquid form. For commercial use, supply by trailer (CH_2 or LH_2 trailer) or pipeline (CH_2) is being considered. Furthermore, it is also possible to generate the hydrogen on-site with electrolysis. Currently, tube trailers carrying vessels at pressure levels between 200 and 500 bars are used to transport CH2. Depending on the material used, the weight-to-volume ratio of the storage vessels varies significantly.

3.7. Alternative hydrogen ferry sizing following Giglio Island stakeholders' inputs in July and August 2024

The above-presented scenario (where a 100 kg hydrogen storage is considered to be installed on board) would enable, as reported in Tab.14, the full "hydrogenation" of the Porto S. Stefano – Giglio/Giannutri service only during the period October – May, when a maximum of 3 trips per day (and with a favourable time scheduling of the ferries that can facilitate the hydrogen refuelling via a swapping procedure) is present.

3.7.1. Increased hydrogen demand and new daily operability of the ferry

Considering an increased H2 onboard storage capacity of up to 400 kg, the operability range of the ferry vessel with a full tank of green hydrogen increases as well, and according to the data of paragraph 4.3, the ferry can operate ideally up to 5 roundtrip journey from mainland to Isola del Giglio.

In the peak season (June September), during the weekends the timetables of Toremar and Maregiglio count up to 7 departures from mainland to Giglio island, managed by two vessels in the time period 8:30-17:30; a single vessel can operate a departure from the mainland every 3 hours, considering the timing to cover a single route of 1 hour, and the timing for disembarking-embarking of the passengers of 30' minutes.

Assuming that a ferry with 400 kg onboard H2 storage operates during peak season up to 4 services per day, we can update accordingly the required amount of green H2 to fuelling the service throughout the year (always considering a swapping "empty for full" procedure of the hydrogen storage to be located on the external decks (if possible, as reported in §4.2, in a superior deck over the cars one, fully dedicated to H2 storage for safety reasons).

The previous table 14 can be then updated as in the following (Tab.16):

Table 8: Porto S. Stefano-Giglio island ferry service schedule, Green H2 demand

	Hydrogen deamnd and ferry servicecoverage Porto Santo Stefano to Isola del Giglio												
	Jan	Feb	Mar	Apr	May	June	July	August	Sep	Oct	Nov	Dec	TOTAL
RoundTrip month	26	24	25	90	93	166	171	175	105	26	26	26	953
RoundTrip/day	1	1	1	3	3	7	7	7	3	1	1	1	na
H2 Trip/month	26	24	25	90	93	120	124	124	105	26	26	26	809
H2 /day [kg]]	80	80	80	240	240	360	360	360	240	80	80	80	na
H2/month [kg]	2080	1920	2000	7200	7440	9600	9920	9920	8400	2080	2080	2080	64720
H2 Ferry %	100.0%	100.0%	100.0%	100.0%	100.0%	72.3%	72.5%	70.9%	100.0%	100.0%	100.0%	100.0%	84.9%

In the peak season, the number of departures from the mainland to Giglio island is five a day during the weekdays (Mon-Fri) and seven a day at the weekend.
The H2 ferry can operate up to 4 trips a day, every day, resulting in a maximum of 120 trips in June and 124 in July and August.
From the table, it is possible to verify the daily amount of green hydrogen to be made available in the year. The H_2 daily need for four roundtrips in the peak season has been considered equal to 360 kg, taking into account a 10% consumption increase for full payload.
The higher operability of the 400 kg tank vessel benefits mostly during the peak season, although a spare vessel (eventually not hydrogen driven) must be available to cover the services at the weekend (that's why the H2FERRY% Services is not 100%).
In the low season, the ferry can operate the single daily roundtrip between the mainland and Isola del Giglio or be engaged in other routes or services considering the longer autonomy of the vessel itself, or it can be operated (without a specific refuelling) for more than one day.

3.7.2. Increased Hydrogen storage capacity on board and impact on the vessel design

The increased capacity of the hydrogen storage, up to 400 kg, has obviously an impact on the weights and volume of the H2 integrated system on board.
As done in §4.2, the possibility to store H2 on board via 350 bar compressed hydrogen storage bottles is foreseen and looking at commercially available solutions (Table 13), the bottles highlighted are the best option targeting a relevant weight ratio and targeting, therefore the installation of 40 bundles for an overall weight of 5360 kg for the hydrogen bottles and around further 600 kg for hydrogen management devices (valves, instrumentations…), the overall increased hydrogen storage system will have a full weight around 6,4 t.

The volume of the 400 kg H_2 storage system (also considering hydrogen management devices to be foreseen) is approximately 20-22 m^3.

This sizing imposes a dedicated deck for the hydrogen storage system, with a relevant steel structure to build up this deck, thus potentially further reducing the covered deck where the cars are parked (an overall reduction between 40-80 m^2 of "parking surface" in the covered deck where cars are parked could be foreseen, thus nothing too remarkable)

3.7.3. Increased hydrogen production on the mainland

With the improved capacity of the vessel and the ability to operate four round trips a day, the green H_2 amount to feed the ferry service increased slightly from annual estimates of 56 tons/year (Table 14, par. 4.3.3), reaching an amount of 65,720 tons/year.

The value remains in line with the potential production of an electrolyser coupled to a 3 MWp PV generator, installed in a region with 1,400 equivalent hours of yearly production and dedicated to producing green H2.

Table 9: Potential green H2 production from a 3MWp PV plant operated in the centre of Italy

	DAILY H2 POTENTIAL PRODUCTION FROM 3 MWp PV GENERATOR IN mid ITALY												
	Jan	Feb	March	April	May	June	July	August	Sept	Oct	Nov	Dec	
	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	
W1	109.2	145.2	169.8	243	237.9	263.7	261.9	262.2	221.1	176.7	169.2	50.1	
W2	154.8	145.8	230.1	175.8	256.8	263.1	262.8	245.7	200.1	174.3	65.1	144.3	
W3	96.9	142.8	221.7	218.1	259.2	258	261	211.8	256.8	109.2	99	93	
W4	169.2	127.2	227.7	231.9	219	263.1	257.1	252	164.7	157.8	57.3	110.1	**Kg/y**
TOTAL	4 111	3 931	6 584	6 516	7 542	7 857	8 082	7 533	6 318	4 790	2 934	3 078	**69 276**

Looking at the required amount of Hydrogen in the peak season, in the months of June. In July and August, there was a production deficit from the 3MWp PV plant. During this period, monthly consumption exceeded 9 tons per month, while PV production was 7.5-8 tons per month.

Table 10: Green H2 production and H2 ferry demand

		Jan	Feb	Mar	Apr	Mag	Giu	Lug	Ago	Set	Ott	Nov	Dic
H2 Ferry demand	H2 /day [kg]]	80	80	80	240	240	360	360	360	240	80	80	80
	H2/month [kg]	2080	1920	2000	7200	7440	9600	9920	9920	8400	2080	2080	2080
PV H2 prod	H2/month [kg]	2 031	2 011	4 584	-684	102	-1 743	-1 838	-2 387	-2 082	2 710	854	998
	H2 excess kg	8 626			-684		-8 050				4 562		

Table 3 above shows the monthly H_2 demand to cover the ferry service and the potential production of H2 from a dedicated 3MWp PV plant.

In the month of April, when the frequency of the trip goes from one per day to three per day, there is a small deficit that is easy to manage, eventually by optimal management of the H2 storage system on the mainland and on board.

During the summer peak season, the amount of H2 to cover the average four roundtrips per day of the H2 ferry is higher than the H2 production of the PV for about 400-600 kg per week.

The 1 MWp electrolyser capacity is able to provide 400 kg of H2 per day if operated 24h, which is ideally possible with proper battery storage to manage the PV production and supply the electrolyser at full power from sunset until the next day.
The power of the PV system is rated to the scope, and a detailed investigation of the green H2 production management can provide optimal solutions in terms of H2 storage system capacity and refuelling management of the vessel.

3.7.4. Potential areas for hydrogen production identified in Porto Santo Stefano

The production of Hydrogen for the supply of the ferry service requires a system with an electrolyser (1MWp), hydrogen storage, and a refuelling station.

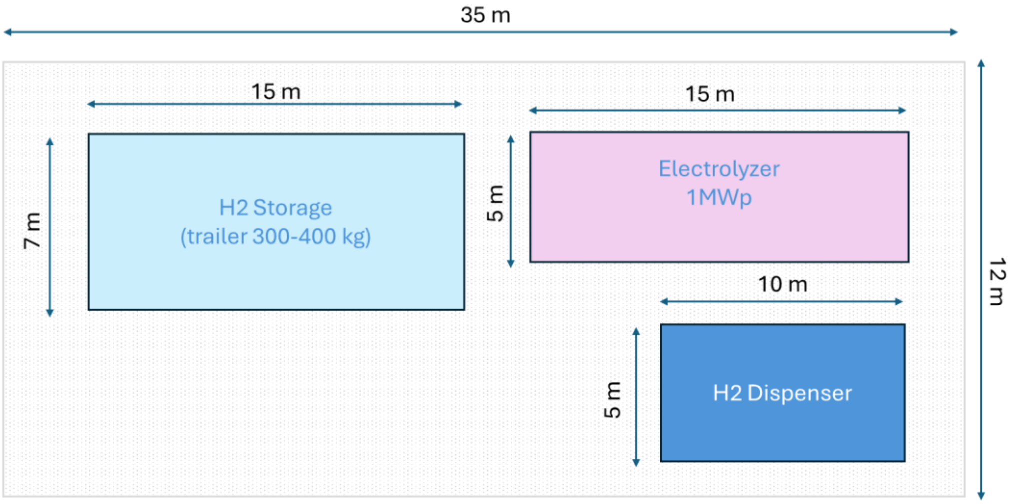


Figure 21: indicative layout of an H_2 production hub and refuelling system, with an indicative footprint of the main components

The system should be ideally located on a pier and possibly at a specific distance from the built environment and public roads.

Regulatory aspects are very specific to the single project's final design; the land utilization in the port area is subject to the Port authority, which can provide the requirements for the identification of a suitable area for a hydrogen ferry refuelling station and, eventually, the availability of spaces on the piers of the port infrastructure.

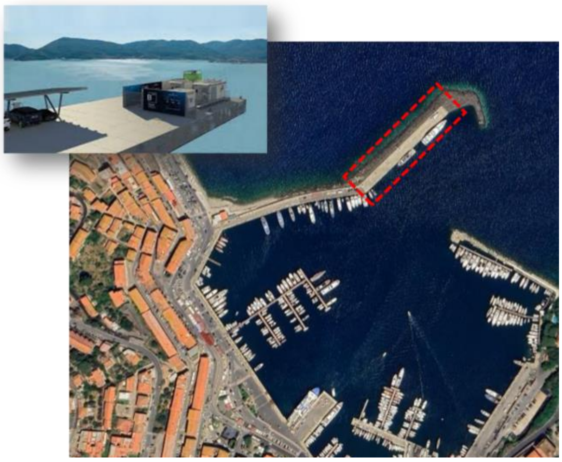


Figure 22: view of the Porto S. Stefano identified deck area in the port and a rendering of a hydrogen refuelling station on a pier (credits Bzero)

3.7.5. Conclusions related to the impact of increasing the ferry H_2 Storage up to 400 kg

Regarding the opportunity to increase up to 400 kg of hydrogen storage to be integrated on board, some final conclusions could be wrapped up.

PROS

- Only a single refuelling during the day in peak time
- Limitation of refuelling time of the H_2 storage (in case of bunkering) thanks to a high flow rate dispenser
- Refuelling area could be foreseen in an area "different" than the boarding one (identified/suggested area), thus limiting issues with the boarding from an O&M and prescriptions point of view
- During the low season, the refuelling of the ferry could be managed with more flexibility and the H_2 produced in the "Green hydrogen hub" can be offered to other local off-takers
- Considering an "H_2 Storage swapping approach", the "two bundles" (as not stationary storage) needed for the swapping could also be used for other hydrogen purposes at the local level to optimise the management of the electrolyser

CONS

- To produce 400 kg/day of hydrogen, the proposed 1 MW electrolyser should operate 24 hours (thus most probably requiring a Renewable Power Purchase Agreement or a full Renewable Net metering approach to guarantee the "Green hydrogen" guarantee)
- According to the PV sizing up to 3 MW, there would be indeed a weekly deficit of around 500 kg of hydrogen (that should be compensated as mentioned above or directly with a hydrogen provision)
- The opposite situation occurs in the Low Season, where an excess of 500 kg/weekly of green hydrogen production is present
- The possibility of foreseeing a hydrogen seasonal storage (thus moving the low season surplus to high season shortage) is not viable as an 8t Hydrogen storage should be locally foreseen; nevertheless, an agreement with a local gas supplier (able to collect surplus in low season and provides hydrogen in peak season) could be considered to be setup

4. Conclusions

This report on the possibility of promoting the transition to hydrogen in part of the fleet operating between Porto Santo Stefano and Giglio-Giannutri.

After an introduction to Fuel Cell and Hydrogen technologies and the opportunities that Hydrogen can offer in the context of short sea distance ferries, the report focused on the assessment of the proposed case study.

According to the analysed operating profiles of the fleet, only the journey between Porto Santo Stefano and Isola del Giglio has been considered, and the possibility of building up a new H_2 ferry to priorly operate along the year on such sailing route has been evaluated by looking at:

- Sizing the overall FC and Hydrogen system to be integrated on board a vessel similar to M/V Isola del Giglio or M/V Dianium (able to transfer both vehicles and passengers) to be newly built (reasons for not proceeding with a retrofitting has been presented)
- Estimation of the overall amount of hydrogen needed along the year to feed in the hydrogen needs of such ferry (according to the time scheduling of the connecting services)
- The potential realisation of a green hydrogen production plant integrated with a Hydrogen Refuelling Station to be installed in Porto Santo Stefano to fuel the ferry

Some Key Performance indicators of the proposed new H_2 Ferry are presented in the next paragraphs, thus showing the pros and cons of the proposed solution in order to enable the island authorities to express their further interest and suitability in the context of Isola del Giglio of looking at this retrofitting opportunity.

All in all, the following main conclusions can be shared:

- From a technical perspective, considering the ferry sailing profile and journey distance (Only 12 nmi), their scheduling (is quite limited along the day, thus allowing refuelling after each round trip) and engine power capacity size (around 1 MW needed as propulsion), the possibility of transitioning to hydrogen one of the ferry of the fleet operating between Porto Santo Stefano and Isola del Giglio seems feasible, as the amount of hydrogen to be stored on board could be limited
- Due to the use of PEMFC (and considering the good solar irradiation of the area), it could be recommended to foresee a self-production of the hydrogen in the Porto Santo Stefano Area in the proximity of the Hydrogen Refuelling Station in order to facilitate the hydrogen logistics and reducing Hydrogen supply costs
- It is relevant to highlight that (not having access to the current fuel costs and O&M cost of the ferry management company), it is not possible to evaluate a Pay Back Period of the proposed investment, which, nevertheless, seems to be significant in this phase without any supporting measure/Incentive that could support at least CAPEX related to the realisation of the vessel.
- Due to the limited number of trips, most of the CAPEX could not be easily paid back by Carbon tax and fuel savings (due to fuel self-production)

BER staff is open to further supporting Isola Del Giglio's community in the potential next steps of this initiative.

4.1. H_2 ferry for Isola del Giglio CAPEX/OPEX

Considering the §4.1 FC system and H_2 storage setup and the possibility to realise a newly built H_2 ferry, the investment needed to realise such vessels can be evaluated as follows (rough estimations)

Table 11: Capital expenditure Hydrogen Ferry, summary

CAPITAL EXPENDITURE ESTIMATION		
Ferry itself	k€	15000 ÷ 18000
Naval certification and regulation aspects (Approval in Principle and RA)	k€	400
Fuel Cell systems	k€	2600
2xH_2 Storage (100 kg – swapping approach)	k€	280
Buffer Battery	k€	150
Power Converters (DC-DC/DC-AC) and DC Link	k€	300
Electric Motors and mechanical auxiliaries	k€	400
Redundant diesel engines and diesel fuel tank	k€	450
H_2 System BoP (Safety devices, instrumentation and controls)	k€	350
Other costs	k€	1000
Total CAPEX	k€	20930 ÷ 23930

While looking at the cost of the potential installation of the Integrated Production and Refuelling plant in Porto Santo Stefano, the following investment could be foreseen

Table 12: Capital expenditure Hydrogen production and refuelling system, summary

CAPITAL EXPENDITURE ESTIMATION		
1 MW ELECTROLYSER delivery + installation & commissioning	k€	1 880
Battery Storage – 3000 kWh (including installation and commissioning)	k€	420
Other expenses (civil works…)	k€	550
H_2 storage and compressor	k€	460
Refuelling station and dispenser	k€	120
PV generator 3 MWp (turnkey)	k€	3 100
Total CAPEX	k€	6530

4.1.1. Economic estimation of the case study foreseeing a ferry equipped with an increased hydrogen storage capacity

If a higher hydrogen storage capacity of 400 kg is foreseen, the overall cost of the ferry actually has a minimum impact, as reported in the table below:

Table 13: Capital expenditure Hydrogen Ferry, summary

CAPITAL EXPENDITURE ESTIMATION		
Ferry itself	k€	15000 ÷ 18000
Naval certification and regulation aspects (Approval in Principle and RA)	k€	400
Fuel Cell systems	k€	2600
2xH_2 Storage (400 kg – swapping approach)	k€	920
Buffer Battery	k€	200
Power Converters (DC-DC/DC-AC) and DC Link	k€	300
Electric Motors and mechanical auxiliaries	k€	400
Redundant diesel engines and diesel fuel tank	k€	450
H_2 System BoP (Safety devices, instrumentation and controls)	k€	450
Other costs	k€	1000
Total CAPEX	k€	21720 ÷ 24720

An interesting aspect to be considered is the fact that the overall proposed hydrogen system would obviously have an impact (in terms of weight and volume) on the payload.

Starting from the fact that the proposed newly built vessel cannot be considered longer than 60 m due to limitations of the piers in the Isola del Giglio port area, a reference case has been considered, targeting the realisation of a vessel with the same tonnage and length of the M/V Isola del Giglio and with a “Hydrogen customised design” as reported in Fig.40.

Table 14: Weights of the Hydrogen Ferry - summary

	100 kg H_2 storage	**400 kg H_2 storage**
Baseline Gross Tonnage	749 t	
Baseline DWT	690 t	
Baseline Payload	595 pax (90 kg each) – 40 vehicles (3,5 t each max)	
Baseline propulsion and fuel storage weight	35 t of fuel oil – 16 t of engines	
Overall weight of the H_2 system	7,8 t	14,2 t
Redundant diesel engine	8 t of engine – 1 t fuel oil	

At the end of the day, as it can be seen since ferries like M/V Isola Del Giglio typically have significant fuel tanks (that enable them not to be refuelled daily), the overall Fuel Cell and Hydrogen (FCH) storage system has no impact on the payload because:

- From a weight point of view, the FCH solution could be even lighter than the MDO/HFO one
- From a volume point of view, as reported in Fig.40, if the H_2 storage is installed in an elevated deck, there should be no significant issues with the reduction of spaces on board for vehicles and passengers (a minimum reduction of the spaces for cars could be maybe foreseen due to a more robust structural need of main deck walls to enable the setup of two elevated decks, one for passengers and one for the H_2 storage)

4.2. Emission savings

Looking at GHG savings, we considered the current fuel consumption of the M/V Dianium and M/V Isola del Giglio to provide the service to Giglio Island.
It is assumed that a fuel emission factor for marine heavy fuel oil, currently in use, is 3.114 tons of CO2 per ton of used fuel, according to Resolution MEPC 245(66).

Table 15: CO2 emissions figures of the vessels providing the 953-roundtrip annual service

CO2 Emissions Ferries 2024			FUEL	CO2
	fuel kg/trip	trip/year	t/year	t/year
Isola Del Giglio	460	733	337.2	1050.0
Dianium	400	220	88.0	274.0
			TOTAL	**1324.0**

Introducing the hydrogen ferry scenario, the emissions will be set to zero for all the roundtrip serviced by the H_2 ferry in case of 100 kg or 400kg H_2 onboard storage.
Table 24 reports the assessment of potential CO_2 emissions in the three scenarios:

1- Baseline (953 roundtrip/year covered by Dianium and Isola del Giglio)
2- H_2 Ferry 100 kg tank (699 roundtrip/year)
3- H_2 ferry 400 kg tank (809 roundtrip/year)

For the case 2 scenario, the CO2 emission saving is about 978 tons/year, equivalent to a reduction of 70%.
For the case 3 scenario, the reduction of CO2 emissions goes up to 1120 tons/year, equivalent to a reduction of 85%, with the present scenario 1(carbon tax assumed ~ 35 €/tCO2).

Table 16: Consumption and emissions figures of the vessels (on the left the baseline, on the right the two H_2 scenarios)

	BASELINE CASE				**100 kg H_2**				**400 kg H_2**			
VESSEL	kgfuel/tr	Tr/yr	tfuel/yr	tCO2/yr	kgfuel/tr	Tr/yr	tfuel/yr	tCO2/yr	kgfuel/tr	Tr/yr	tfuel/yr	tCO2/yr
Isola d Giglio	460	733	337	1050	460	164	75,4	234	460	-	-	-
Dianium	400	220	88	274	400	90	36	112	400	164	65,6	204,3
H_2 FERRY	80	-	-	-	80	699	56	0	80	789	64	0
	TOTAL	953		1324	**TOTAL**	953		346	**TOTAL**	953		204,3

4.3. Potential incentives and supporting measures

Considering the significant investment needed to set up a hydrogen ferry solution in Isola Del Giglio/Porto Santo Stefano (more than 20 M€ for the ferry and a further 6.5 M€ for the green hydrogen production hub), it is crucial to look for potential incentives and support measures that can support the realisation of this project.

First of all, it is important to acknowledge that the setup of a local green hydrogen production site is something more than relevant but absolutely economically convenient to guarantee a proper management of the hydrogen ferries.

The overall investment is certainly relevant, but once operative, the plant would have limited O&M costs (around 200k€ for personnel and some O&M): the alternative would be to set up a local (on the Porto S. Stefano Pier) or portable Hydrogen Refuelling Station (CAPEX around 1 M€) where the required amount of H_2 is daily delivered by hydrogen trucks.
This solution is logistically (and environmentally) less sustainable, but it is also more expensive at the end of the day, considering that the cost of daily delivery of H_2 5.0 quality (to be used in PEMFC) can today cost between 15 and 20 €/kg, thus with an annual OPEX of H_2 delivered between 1 and 1.3 M€ (depending on the H_2 storage capacity and the final H_2 costs).

Considering the significance of the foreseen investments and the lack (to our best knowledge) of dedicated incentives at the national level for this kind of project, the most relevant financing instruments currently available at the European level could be:

- **INNOVATION FUND** - https://cinea.ec.europa.eu/programmes/innovation-fund_en : financed by EU Emissions Trading System revenues, is one of the world's largest funding programs for the demonstration of innovative low-carbon technologies. The Fund focuses on highly innovative clean technologies and major flagship projects with European added value that can lead to significant reductions in emissions and greenhouse gas emissions.
  Innovation Fund projects cover a wide range of innovative technologies in areas such as energy-intensive industries, renewables, energy storage, net-zero mobility and buildings, hydrogen, and carbon capture, use and storage.
  Projects related to the maritime sector (a "new ETS sector") and hydrogen promotion are usually well received.
- **CEF (Connecting European Facility) for transport and Infrastructure funds** - https://cinea.ec.europa.eu/programmes/connecting-europe-facility_en: a funding instrument to realise European transport infrastructure policy, with a focus on waterborne and port infrastructure too. It aims at supporting investments in building new transport infrastructure in Europe or rehabilitating and upgrading the existing one. The funding intensity is about 25% of the claimed costs (CAPEX and OPEX) of the proposed project.
  Projects related to hydrogen promotion in transport and infrastructure sectors are usually quite well welcome

Other type of funding schemes (like HORIZON and Clean Hydrogen Partnership projects, regional/national (in case they would appear) and inter-regional funds like INTERREG MARITTIMO) should be considered only foreseeing blending of different financing schemes (if manageable according to funding rules).

4.4. Final recommendations

Generally speaking, the proposed route (Porto S. Stefano and Isola del Giglio) and type of ferry could be quite easy to be "hydrogenised" from a technical point of view.

Considering the complexity of integrating onboard hydrogen storage in open decks without limiting the payload, the potential retrofitting of one of the available vessels (e.g. M/V Isola del Giglio or M/V Dianium) would not be possible thus a newly built “hydrogen ready” vessel is suggested, with specs similar to M/V Isola del Giglio ones, also considering the limitations to vessel’s length up to 60 m in the port of Isola del Giglio.

This is, of course, a more “CAPEX intensive” option, but this is currently the most feasible opportunity.

In this sense, starting from data shared by MareGiglio, a Fuel Cell-based power propulsion system was proposed in Chapter 4, looking at the possibility of integrating on board or 100 kg or 400 kg hydrogen storage, with different impacts on the “Hydrogen coverage” of the whole year routes.

For it concerns the evaluation of hydrogen supply, the possibility of self-produce green hydrogen in “mainland areas” close to Porto S. Stefano is suggested considering the daily/weekly for the ferries: For this purpose, a specific analysis was performed also foreseeing the integration of a HRS (fixed or mobile) to directly bunker the vessel or to fill up bundles that should be then transferred on board (via a “full/empty” swapping approach). Such HRS could be open to another type of H_2 users (particularly in the wintertime when the daily need for H_2 from the ferries is lower; thus, H_2 production could be proposed to other local off-takers).

What is for sure clear is that the hydrogen opportunity to decarbonise the Isola del Giglio/Mainland connection ferries is more valuable than the possibility of integrating batteries on board, mostly due to the fact that the weight and volume of batteries needed would significantly reduce the payload of the vessel, while the hydrogen solution has no major issues in this sense.

The possibility of producing power onshore via a fuel cell genset generator to be then transferred in a “cold ironing approach” to a battery-based ferry is, at the end of the day, a non-valuable option, mostly for volume/weight limits of battery-equipped ferries as mentioned above.
Furthermore, the possibility of producing power “onshore” would require the setup of a Hydrogen Storage on the docks, posing challenges from a health safety and regulatory perspective as well as to the logistics of bringing and storing daily significant quantities of hydrogen on the docs

For sure, the “refuelling of the ferries” is a challenge (mostly due to refuelling timing – around one hour – and the safety prescriptions for refuelling procedures in ports), but the possibility of working with “swapping solutions” could be an approach to overcome such aspect.

Another challenge of having hydrogen on board the ferry is obviously the regulatory framework: the fact that the vessel is operating in a limited routing (and for sure in Italy only) could, in any case, open opportunities to get special permits from the Italian Flag Authority and (for sure) an Approval in Principle by Naval Classification Societies.

References

In addition to references integrated along the text as footnotes, BER would like to acknowledge the following relevant sources of information

- Fuel Cell Systems for Marine Applications, PhD Thesis, Eng. Thomas Lamberti, University of Genova 2018.
- Assessment of a Fuel Cell A.P.U. system with reduced environmental impact for marine applications, Bachelor Thesis, Eng. Thomas Lamberti, University of Genova 2012.
- Alternative low-emission power generation system for short sea shipping, Master Thesis, Eng. Thomas Lamberti, University of Genova 2015.