Scicluna, D. et al. (2024). *Xjenza Online*, 12(2):121–134.

Xjenza Online: Science Journal of the Malta Chamber of Scientists
www.xjenza.org
DOI: 10.7423/XJENZA.2024.3.03

Research Article

Identification of Candidate Sites for an Offshore Green Hydrogen Production Plant Concept with Integrated FLASC Energy Storage in Malta's Exclusive Economic Zone

D. Scicluna[*1], **O. Pirotti**[1], **R. N. Farrugia**[1], **T. Sant**[2], **D. Buhagiar**[3]
[1]*Institute for Sustainable Energy, University of Malta, Malta*
[2]*Department of Mechanical Engineering, University of Malta, Malta*
[3]*FLASC B.V., Netherlands*

Abstract. The integration of Hydrogen (H_2) production systems with offshore renewable energy (RE) generation could create opportunities for future decarbonisation of the maritime sector. However, the intermittency of wind and other offshore renewables presents several challenges with respect to power generation and electrolyser shutdowns and start-ups. In such situations, it could be advantageous to integrate energy storage systems (ESS) to ensure, as far as possible, the uninterrupted operation of stand-alone offshore systems by balancing the renewable electrical power surpluses with the deficits, or shortfalls. The Floating Liquid Piston Accumulator using Seawater under Compression (FLASC) technology, a patented Hydro Pneumatic Energy Storage (HPES) system specifically designed and developed at the University of Malta for marine deployment, was the ESS of choice for integration into an offshore green hydrogen production plant. This research report is related to the HydroGenEration ("*Hydro-pneumatic Energy Storage for Offshore Green Hydrogen Generation*") project that investigates the feasibility of using the FLASC storage technology for hydrogen production subject to Mediterranean wind conditions. Apart from the technical feasibility, a necessary requisite for a stand-alone, offshore hydrogen production plant is the identification of suitable offshore sites and of potential end-users, such as maritime sector operators as consumers of the H_2 fuel. Project HydroGenEration explores potential deep-water sites in the central Mediterranean basin, and specifically in proximity of the Maltese Archipelago, as a basis for more representative numerical modelling of the technology concept. A high-level candidate site identification exercise was therefore conducted. The zones identified as potential candidate sites for the HydroGenEration project concept were predominantly within the areas declared in the more recently launched 2023 document: "National Policy for the Deployment of Offshore Renewable Energy - A Draft for Public Consultation", defining the future role for offshore renewables in Malta's Exclusive Economic Zone (EEZ).

Keywords: Floating Wind; Green Hydrogen; Energy Storage, Electricity Stabilization

1 Introduction

Research aimed at decarbonizing industry and the transport sectors, especially marine transport, can contribute significantly to achieving greenhouse gas (GHG) emissions reductions. Optimizing the efficiency and economic feasibility of the hydrogen (H_2) and green hydrogen fuel production process in particular, its storage, transportation, and use, can create the right conditions for the development of a renewable, clean, carbon-free economy,

ECU—Energy Conversion Unit
EEZ—Exclusive Economic Zone
ESS—Energy Storage System
ERA—Environment and Resources Authority
EWA—Energy and Water Agency
FLASC—Floating Liquid Piston Accumulator using Seawater under Compression
HPES—Hydro Pneumatic Energy Storage
HGE—HydroGenEration
PCS—Pressure Containment System
PEM—Proton Exchange Membrane
SAC—Special Areas of Conservation
SPA—Special Protection Areas
SWH—Significant Wave Height

*Correspondence to: D. Scicluna (diane.scicluna@um.edu.mt)

especially in the case of the maritime transport sector. The use of hydrogen as a fuel in this sector represents a new, environmentally-friendly mode of non-polluting global transportation.

One way to produce hydrogen using renewable energy resources is by means of the electrolysis process. It consists of the splitting of water into hydrogen and oxygen by using electricity. Using electrolysis promises economic and environmental benefits if supplied by electricity coming from renewable sources (Ahmed et al., 2024; Gao et al., 2022; Zaini et al., 2023). In addition, the 'green' hydrogen produced will allow for the replacement of fossil fuels in those sectors of the economy in which direct electrification is currently not possible, and which will depend on the availability of a physical fuel for an indefinite time in the future.

Hydrogen production through electrolysis using treated water and electrical energy is an established process. The challenge of using renewable sources such as solar and wind to supply such plant is the resources' inherent intermittency. This not only results in lower efficiency of the hydrogen production plant equipment and a reduction in the amount of hydrogen produced but in addition, the amount of "ON"/"OFF" cycles causes degradation of the electrolyser cells and consequently results in more frequent equipment replacements, ultimately affecting the cost of hydrogen produced. Issues with "ON"/"OFF" cycling is further highlighted in (Honsho et al., 2023; Kojima et al., 2023; Weiß et al., 2019).

And who are the end-users? For example, the prospect of converting a fishing fleet to the use of hydrogen as a fuel for motive power would lead to a significant reduction in Carbon Dioxide (CO_2) emissions into the atmosphere, resulting in improved living conditions for marine organisms and an increase in the quantity and quality of fish landings. Maritime passenger travel and freight transportation is not an environmentally-friendly industry. Studies show that some of the largest ships produce more Nitrous Oxide (N_2O) and Sulphur Dioxide (SO_2) emissions per year of operation than all road vehicles. In 2021 alone, such emissions increased by 833 million tons of CO_2; an increase of 4.9% (European Marine Observation and Data Network, n.d.).

After consultations, the International Maritime Organization (IMO), together with the UN Shipping Agency, decided to limit SO_2 emissions from 2020. In 2021, the European Parliament included maritime shipping in the EU Emissions Trading Scheme (IMO, 2021, 2023). Creating additional routes for ships as well as implementing international policy tools to accelerate the development of fleets equipped with fuel cell engines could help make this industry a potential consumer of hydrogen fuel.

The Mediterranean Sea is a link between major sea-lanes connecting Europe, North Africa, and the Middle East. The Mediterranean Sea is connected to three major maritime transport passageways namely the Strait of Gibraltar, the Suez Canal, and the Bosporus. Therefore, the Mediterranean Sea is an important element of modern maritime transportation routes and is also a link between Asia and Europe (Plan Bleu, 2021). The Maltese Islands are strategically positioned in these shipping corridors.

The present research report discusses part of the work undertaken in the nationally-funded project HydroGenEration, which explored the potential for implementing offshore green hydrogen production integrated with energy storage in the vicinity of the Maltese islands. The scope of integrating the FLASC energy storage device is to close the gap between the fluctuating renewable energy (RE) electricity supply and the electrical requirements, or load, imposed by an islanded offshore H_2 production system. The FLASC concept was also investigated in the following earlier works (Borg et al., 2023a; Buhagiar & Sant, 2017; Cutajar et al., 2021; Settino et al., 2022). Integrating FLASC into the green H_2 production process would allow for an improved decarbonised offshore hydrogen production process. But this does not stop here; producing the H_2 in that same environment which supplies the raw material itself, i.e., seawater, and producing a clean fuel that can be used by nearby end-users, offer additional benefits and reductions in production and supply chain emissions.

This research project also focused on the identification of candidate sites for the HydroGenEration project concept based on various technical and geophysical criteria and constraints. These include the climatology and the bathymetric features of the seas around the Maltese archipelago, environmental aspects and the identification of stakeholders driving the diverse economic activities underway in territorial waters, in the Fisheries Management Zone and farther afield in the Exclusive Economic Zone (EEZ). Such prospects were defined in the "Preliminary Market Consultation – PMC for the proposal of economic activities within Malta's Exclusive Economic Zone" (Continental Shelf Department, 2022), which served as a basis for the shortlisting of potential candidate sites for the HydroGenEration project concept.

More recently, sites for offshore renewable energy projects were also defined in the "National Policy for the Deployment of Offshore Renewable Energy - A Draft for Public Consultation", (Energy and Water Agency & Ministry for the Energy, Environment and Regeneration of the Grand Harbour, 2023), which confirmed that the methodology used for the HydroGenEration site selection process had been sound.

The scope of this research report is to highlight some

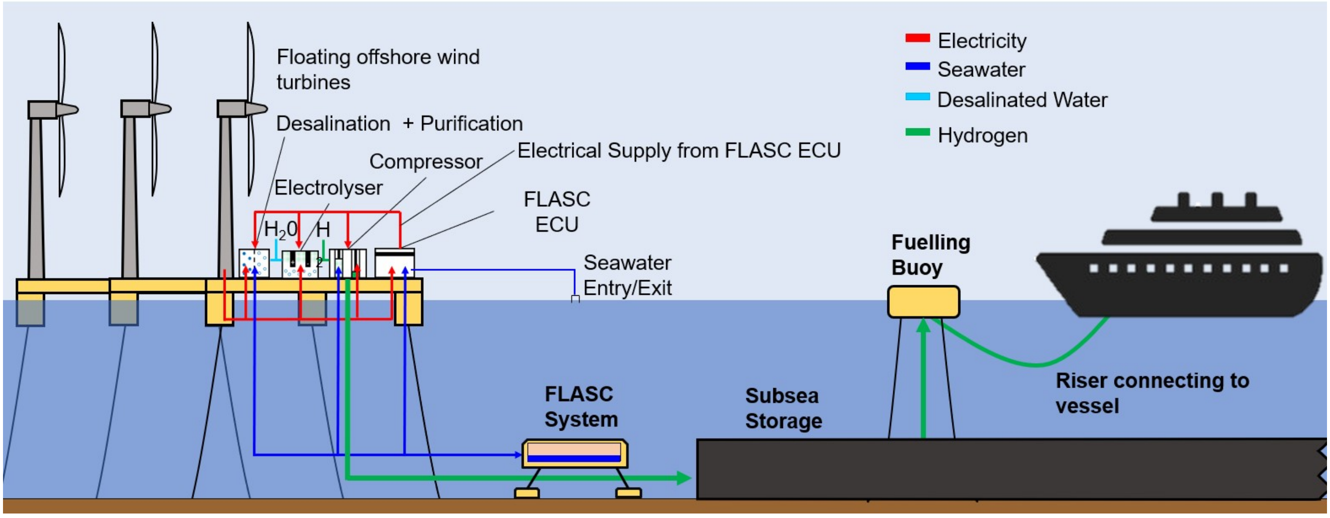

Figure 1: The HydroGenEration project concept system showing a modular three wind turbine "cluster" which was used as a basis for the numerical modelling.

of the main challenges for implementing offshore wind in the Mediterranean Sea. Furthermore, this also aims to highlight the technical benefits associated with implementing an energy storage system (ESS) such as FLASC with respect to the intermittency of renewable energy resources and its effect on the "ON"/"OFF" cycles of the electrolyser. Finally, this study also highlights the process undertaken for the candidate site assessment part of the project. Finally, the research project also identifies the potential end users that will benefit from the hydrogen produced.

The concept of offshore floating platforms has been well established by the Oil and Gas Industry. In recent years, the original idea has expanded to include the concept of multi-integrated floating platforms and technologies such as energy islands as those found in Denmark (Danish Energy Agency, 2023). Energy islands consist of artificial islands that are used as a hub for offshore wind farms in order to facilitate better connections between the electricity generated and the energy system in the surrounding area. Other related projects and technologies that are making use of similar concepts are the Jidai concept (DNV, 2015), the Sealhyfe project (Lhyfe, 2023), the Aquaventus project (Aquaventus, 2024), the Dolphyn Hydrogen project (Dolphyn Hydrogen, 2024), the Wind4H2 project (Settino et al., 2022) and the MUSICA project (MUSICA, 2024).

2 Materials and Methods

The HydroGenEration (HGE) concept built on earlier experiences gained in the WIND4H2 project (Settino et al., 2022). In the current HydroGenEration system (Figure 1) the concept system 'cluster' would consist of:

i) three 10 MW floating offshore wind turbines (WTs) which can, at any stage, be replicated in a modular way to upscale the H_2 production concept system;
ii) a floating WT platform-mounted water Desalination and Purification plant, an Electrolyser and an Ionic Compressor;
iii) a floating WT platform-mounted FLASC Hydro Pneumatic Energy Storage (HPES) system consisting of a topside ECU and a seabed-mounted Pressure Containment System (PCS). This latter module will be connected to the topside ECU by means of electrical and hydraulic risers; and
iv) a H_2 storage system with one or more floating refuelling stations. The H_2 storage system will be placed on the seabed and the refuelling station/s will be moored in a vessel berthing/refuelling zone.

For the scope of the HGE project, the scaled-up concept system would consist of a 10 x 10 MW WT array comprising three identical HGE concept system clusters and one additional wind turbine.

The results of a Decision Matrix compiled for this part of the study identified and enabled justification of potential locations suitable for the hybrid concept project for integrating a deep offshore wind farm, energy storage and hydrogen production units to sustain an offshore green hydrogen production plant and offshore refuelling station.

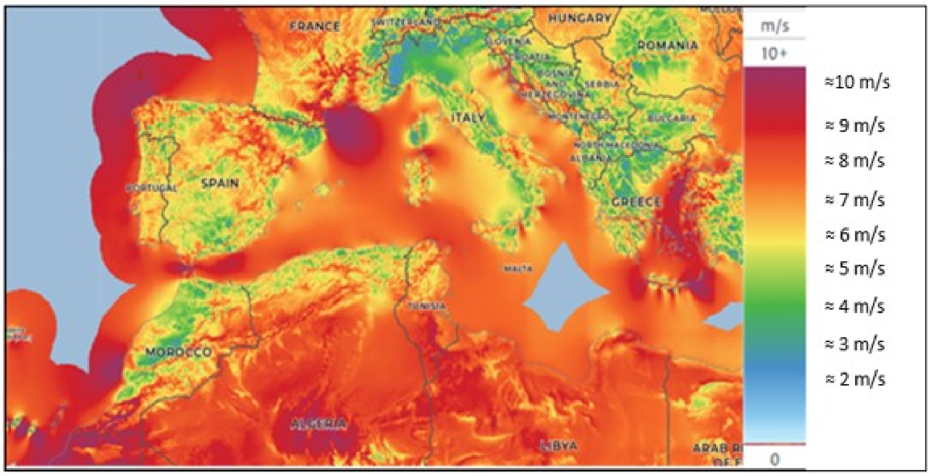

Figure 2: Wind resources at a height of 100 m in the Mediterranean Sea (Global Wind Atlas, 2023).

2.1 Metocean Conditions of the Mediterranean Sea

The wind climate in the central Mediterranean is more variable compared to that in the North Sea, but despite its lower wind speeds and higher variability, the Mediterranean still offers a reasonable potential for RE generation, as shown in Figure 2 (Davis et al., 2023) where the long-term wind speed at a height of 100 m is shown.

The sea depths around the Maltese islands, and especially within Malta's Exclusive Economic Zone (EEZ), present a significant challenge to introducing offshore wind turbines. At such sea-depths, traditional bottom-fixed structures are not viable, making floating structures the only remaining option. Floating structures for wind turbines can allow access to marine spaces having greater sea depths, which are located farther away from the shore. By increasing the distance of the wind plant from shore, the floating turbines will encounter stronger and less turbulent winds, allowing for increased electrical power generation. However, the costs associated with mooring, installing and operating floating offshore wind turbine support structures necessitate a compromise between the sea depth and the distance from ports and harbours, while also striving to maximise energy capture. If such an RE generation plant were to be connected to the onshore grid network, then such costs would increase significantly with distance to shore.

In addition to the sea-depth, it was also important to consider the metocean conditions at deep offshore sites for such a project concept. The term 'metocean conditions' refers to local surface winds, wind-generated surface waves, swells and ocean surface currents, deep water currents and basin circulation, amongst others. Although seawater is abundant and readily available for use in an offshore hydrogen production process, the lifetime of the H_2 production system components may be significantly shortened due to the high salinity of the Mediterranean Sea, thereby increasing the cost of additional system components, their maintenance, and their replacement.

The Mediterranean Sea is a comparatively small and partially-enclosed sea, which affects the characteristics of the sea waves generated within. The average wave period in the Mediterranean Sea was found to be of around 6 to 8 seconds and so, significantly shorter than waves in open ocean areas where wave periods can be between 10 to 20 seconds or more (Drago, 2006; Environment and Resources Authority, 2013; Galdies, 2022; Transport Malta, 2013). Studies have shown that on average, the significant wave height (SWH) around the Maltese Islands does not exceed 2.5 m, and that SWHs generally occur during the winter months (Drago, 2006; Environment and Resources Authority, 2013; Galdies, 2022; Transport Malta, 2013). The less extreme wave heights occurring in the seas around the Maltese Islands are advantageous when compared to conditions in the North Sea, where the offshore wind sector is thriving, given that floating offshore structures are required to be resilient and to have a safe clearance between the maximum wave height and critical components. However, storms referred to as medicanes, do occur in the Mediterranean Sea. Although such storms are not a common occurrence, medicanes present a natural occasional hazard and can induce increased wave heights, posing significant challenges to the design and operation of fixed and floating offshore structures (Galdies, 2022).

Another important factor to consider is the seabed around the Maltese Islands. According to data obtained from various studies, the north-eastern coastal zone of the Maltese Islands is characterised by gently sloping topography, which transitions offshore as a gently sloping rocky bottom. Further offshore, the sea-bed constitution changes from sedimentary rock to a mixture of sand, cobbles, pebbles and small boulders. In certain areas, patches are also covered by a thin layer of sand (Foglini et al., 2015; Micallef et al., 2013).

In contrast, the southwest side of the Maltese islands' coastlines are made up of cliffs and an accumulation of weathered rock fragments at the foot of these cliff faces, otherwise known as boulder screes (Foglini et al., 2015; Micallef et al., 2013). Such characteristics are important to consider as they can affect the type of mooring anchors which can be used for offshore floating structures, subsequently also affecting the overall project cost. Sea depths also increase much more significantly close to the coast on this side of the island group.

2.2 Interfacing of the FLASC Energy Storage System

The incorporation of an ESS such as FLASC into the HydroGenEration concept strives to address one of the largest issues present in the renewable energy industry i.e., that of intermittency of renewable energy sources. The FLASC system consists of two core modules:

i) the Energy Conversion Unit (ECU), and
ii) the Pressure Containment System (PCS).

The ECU system consists of a modular hydro-electrical interface which houses the pumps, hydraulic turbines, controls and power conversion equipment required for a HPES system. Meanwhile, the PCS consists of pressure vessels providing a storage volume for seawater and compressed gas (air in this case), in a pre-charged state.

In order to incorporate the FLASC ESS into the offshore wind turbine design, it is important to take into consideration the requirements of the FLASC system with respect to the metocean conditions in the Mediterranean Sea. One of the requirements of the FLASC system in its closed cycle configuration is that the system is more adapted for installation in waters not much deeper than 100 m and such a factor was also taken into consideration when conducting the assessment of potential candidate sites for the HGE concept system.

Given that the system will be installed in waters of up to a 100 m depth, it would also be possible to use the deep seawater having lower temperatures present at such sea depths to the system's advantage. The cool deep seawater being used in the PCS can be extracted and used as part of the water desalination and cooling processes in the hydrogen production system.

The behaviour of the FLASC ESS was tested under measured high resolution wind scenarios using scheduling windows of different durations. The term 'scheduling window' refers to the time frame during which uninterrupted electrical power is fed to the plant equipment provided by the FLASC ESS. Subsequently, these techniques were also used in the optimization of the HGE concept system.

2.3 Hydrogen End users in the Mediterranean Sea

In identifying maritime sector operators that may switch to hydrogen fuels in the coming decades, various facets of the maritime sector should be considered. Fishing is one of the backbone industries of Mediterranean Basin economies. Of course, this sector is closely linked to offshore zones and will therefore be near any future offshore sources of renewable electricity generation. The diversity of the underwater world has contributed to the development of the small-scale commercial fishing fleet. This sector accounts for about 85% of the total fishing industry. Fishing in the Mediterranean Sea typically takes place at sea depths ranging from 10 to 800 meters. Given the comparatively greater depths of the Mediterranean in coastal areas, most fishing is concentrated closer to the shore and up to depths of about 400 meters (Food and Agriculture Organization of the United Nations, 2022).

Malta's own fishing fleet consists of some 2,741 vessels, the vast majority of which are small, coastal fishing vessels. Overall, 46% of the vessels are less than 5 meters in length. Meanwhile, another 49% of such vessels boast a length of up to 9 meters. About 4% reach lengths of up to 14 meters. Less than 1% of the total reach lengths of 15 to 19 meters and more than 20 meters combined. Only 25 of all fishing vessels are trawlers. Vessels rely on diesel or diesel-electric, gasoline and very rarely benzene engines for their motive power (National Statistics Office, 2022b).

In order to promote the transition of marine vessels to hydrogen propulsion for motive power, it is important to involve all stakeholders in developing green maritime policies, developing a chain of marine hydrogen plants integrated with energy storage systems, and the setting up of offshore hydrogen refuelling stations with a standardised refuelling system for ships.

2.4 Assessment of Potential EEZ Candidate Sites

When considering potential sites for implementing floating offshore wind turbines, energy storage and co-located H_2 production, storage and refuelling infrastructure, it is necessary to ensure that such a plant would be able to coexist with other existing or future offshore installations, with marine leisure and maritime industrial activities, as well as be capable of operating in the vicinity of environmentally sensitive or protected sites. An Exclusive Economic Zone

(EEZ) has been defined as "an area that extends beyond the country's territorial waters and that partially or fully coincides with the continental shelf of the country, without prejudice to a final designation of the zone itself" (Grech, 2022).

In project HydroGenEration, a high-level site identification exercise was conducted based upon the Malta Government Continental Shelf Department's report: "Preliminary Market Consultation for the Proposal of Economic Activities within Malta's Exclusive Economic Zone", published in 2022 (Continental Shelf Department, 2022).

According to the Malta Maritime Forum (MMF), the ideal designation for the EEZ's Area 1, comprising of Hurd's Bank, should be retained for shipping purposes, such as marine traffic and anchorages. On the other hand, the EEZ's Area 2 was defined as an ideal area for implementation of marine projects, such as floating alternative energy installations, aquaculture projects and refuelling infrastructure.

Site selection is one of the most crucial parts of any candidate project and research such as Cradden et al. (Cradden et al., 2016) and Diaz et al. (Diaz et al., 2018), were used as a guide to determining the criteria for the site selection process of an offshore wind farm.

For the preliminary site selection of a hybrid offshore project such as the one being conceptualised by project HydroGenEration, a number of different technical and environmental aspects were taken into consideration, such as:

- proximity to ship bunkering sites (Transport Malta);
- distance from the shoreline;
- proximity to maritime shipping and leisure routes and corridors (Planning Authority, 2016);
- exposure to local wind conditions (National Statistics Office, 2022a);
- exposure to sea waves (National Statistics Office, 2022a);
- dependence on bathymetric characteristics (Continental Shelf Department, 2022);
- requirements for seabed conditions (Environment and Resources Authority, 2013);
- proximity to environmentally sensitive sites (such as NATURA2000 sites, Special Areas of Conservation (SACs) and Special Protection Areas (SPAs)) (Environment and Resources Authority, 2023);
- co-existence with fisheries and aquaculture sites (Food and Agriculture Organization of the United Nations, 2022), and
- simplified wind turbine array layout designs.

In addition to the criteria presented above, it is critical to keep in mind the different sea-depth characteristics present within the two designated areas, defined as Area 1 and Area 2, within the EEZ.

Array	Type	Crosswind Spacing	Downwind Spacing	Approx. Array Length [km]	Approx. Array Width [km]
1	Linear	$6 \times D$ 1,200 m	-	10.8	0.2
2	Rectangular	$6 \times D$ 1,200 m	$9 \times D$ 1,800 m	4.8	1.8

Table 1: Key dimensions used for the two types of simplified wind turbine arrays, each having 10×10 MW wind turbines (where D is the WT rotor diameter).

Given that the current research project is focusing on floating wind turbines and on seabed-mounted energy storage along with hydrogen production and H_2 fuel storage systems, it was reasonable to assume that costs for site surveying, preparation, installation, mooring and anchoring, maintenance, and decommissioning at end of life, will all increase significantly for increasing sea depth. The proposed HydroGenEration concept system is intended to be off-grid, meaning that it will not be connected via cable/s to an onshore electricity distribution network or to land-based consumers. Conversely, by moving further offshore and out of the 'land shadow', it would be possible to access stronger and more consistent winds for increased renewable energy (RE) electricity generation. Consequently, it would be important to achieve a balance between distance from the shore and sea-depth. In order to achieve a compromise between costs, wind resources and environmental conditions, areas having sea depths in excess of 200 m were excluded from the site identification process. Additionally, at this stage the intention is not for the offshore hydrogen being produced to be conveyed by pipeline towards the shore, but to be stored offshore subsea and to supply maritime end-users or bulk H_2 carriers with the H_2 fuel by means of one or more refuelling buoys.

Therefore, the proposed sites were also zoned closer to the offshore designated ship bunkering sites so that seagoing vessels anchored there could be one of the potential end-users. The wind turbine arrays were simplified assuming two arrangements, namely:

i) a linear array and
ii) a rectangular arangement (see Table 1).

These arrays were designed to give maximum exposure to the individual turbines under prevailing wind conditions in the vicinity of the islands, i.e., for winds blowing from the West to Northwest sectors. Consequently, the arrays

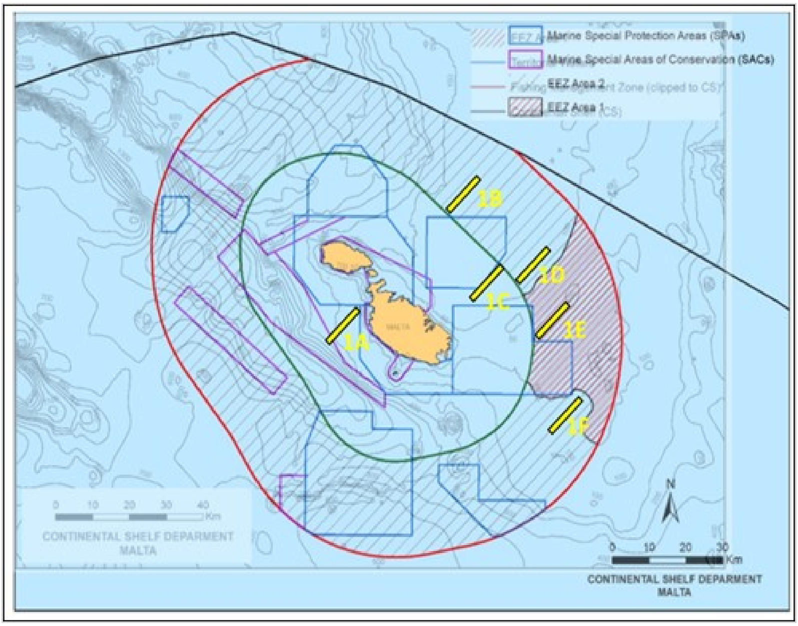

Figure 3: Visual Representation of the Linear Array considered in the HydroGenEration project. Base maps with kind permission of the Continental Shelf Department (Continental Shelf Department, 2022).

Weighting	Candidate Site Classification
1	Low — Not ideal
2	Intermediate — Offer some benefits
3	High — Offers a lot of benefits
4	Ideal — Ideal site

Table 2: Weighting factors used for shortlisting the candidate sites for the two types of simplified wind turbine arrays, each having 10 × 10 MW wind turbines.

were also placed in a single or double linear arrangement whose main axes run perpendicular to these wind directions.

The two proposed WT arrays were for 10 x 10 MW turbines having a rotor diameter (D) of 198 m and a hub height of 119 m, based on NREL's 10 MW wind turbine characteristics (IEA, 2020). The single linear array can be seen in Figure 3.

A number of different activities underway around the Maltese Islands were considered in this high level analysis. These included activities such as harbour approach routes, protected areas and more. In order to select the ideal candidate site/s for the proposed HydroGenEration project concept, a decision matrix listing all of the criteria or factors considered was mapped out. The criteria were ranked with a weighting ranging from 1 to 4, with number 4 being the most attractive (see Table 2).

3 Results and Discussion

3.1 Estimates of Amount of H_2 Produced

In order to numerically model these scenarios, preliminary calculations for the developed numerical model were run. Wind conditions from the University of Malta's coastal onshore Light Detection and Ranging (LiDAR) wind measurement system (Environment and Resources Authority, 2023) were used to represent wind conditions aloft. The wind speed time series was corrected by a factor of + 0.3 m/s to correspond to offshore wind conditions. The average wind speed at a height of 111 m for the 12-month time frame (year 2016) was computed to be 6.8 m/s. This data enabled modelling of the HGE system behaviour with a 10-minute resolution time series for modelling offshore WTs rated at 10 MW and having a hub height of 119 m. The power curve for the modelled wind turbine was obtained from (IEA, 2020).

The wind data obtained from the coastal LiDAR database confirmed the information about the lower speeds in the Mediterranean basin compared to those in the North Sea as well as higher wind variability, making the data suitable for further processing as a feed into the HGE system numerical models for Mediterranean Sea categorisation. In the case of the wind-generated electricity, wind turbine array wake losses and plant availability were taken as 95% respectively.

The conversion of wind speed into WT power output was carried out using a mathematical model for the 3 wind

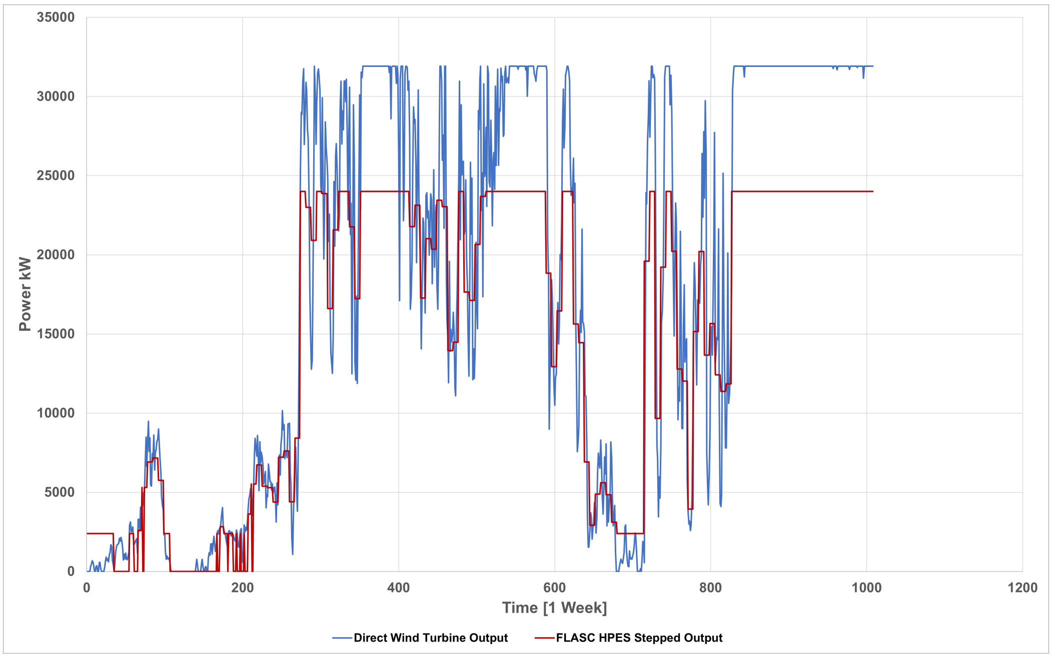

Figure 4: Direct wind turbine output in comparison with the FLASC HPES stepped output in Mediterranean wind conditions for a random week.

turbines, each with a nominal capacity of 10 MW, and similar to that used in earlier work (Settino et al., 2022) for the North Sea offshore wind data. The capacity factor of the wind farm under Mediterranean wind conditions was found to be 38%. These calculations confirm that wind speed and the resulting energy yield in the North Sea are higher than in the Mediterranean, and also show a more intermittent nature of wind in the Mediterranean, thus further highlighting the need for an ESS to smoothen the renewable electrical supply.

Figure 4 illustrates a comparison of the electrical power generated by 3 x 10 MW wind turbines to the power supplied by the same WTs coupled to a FLASC ESS and the resulting smoothened power output under Mediterranean Wind conditions over a period of 7 days. As shown in Figure 4, the use of the HPES system allows for the number of occurrences where the power supply drops to zero to be decreased significantly, thereby stabilising the supply of electricity to the hydrogen production unit.

In order to understand the effects of incorporating the FLASC ESS into the hydrogen production system, a number of simulations were carried out. The simulations investigated the effect of FLASC on the amount of hydrogen produced as well as on the number of "ON"/"OFF" cycles experienced by the electrolyser. From these simulations it was possible to obtain an optimised configuration for the HydroGenEration concept cluster.

The parameters for the optimised HGE system are listed in Table 3. In this series of computations, the trend

FLASC ESS Capacity (MWh)	25
Number of "ON"/"OFF" Cycles	
without storage	1,263
with FLASC storage	435
Total H_2 produced (kNm^3/year)	
without storage	17,761
with FLASC storage	17,820
% Diff.	0.3%
Total Energy Required (MWh)	
without storage	90,939
with FLASC storage	91,240
Total energy produced by WTs	98,625
Curtailed Energy (MWh)	
without storage	7,686
with FLASC ESS storage	7,384
Electrical Energy lost due to overproduction	
without storage	7.8%
with FLASC storage	7.5%

Table 3: Ideal parameters for the HydroGenEration concept 'cluster'.

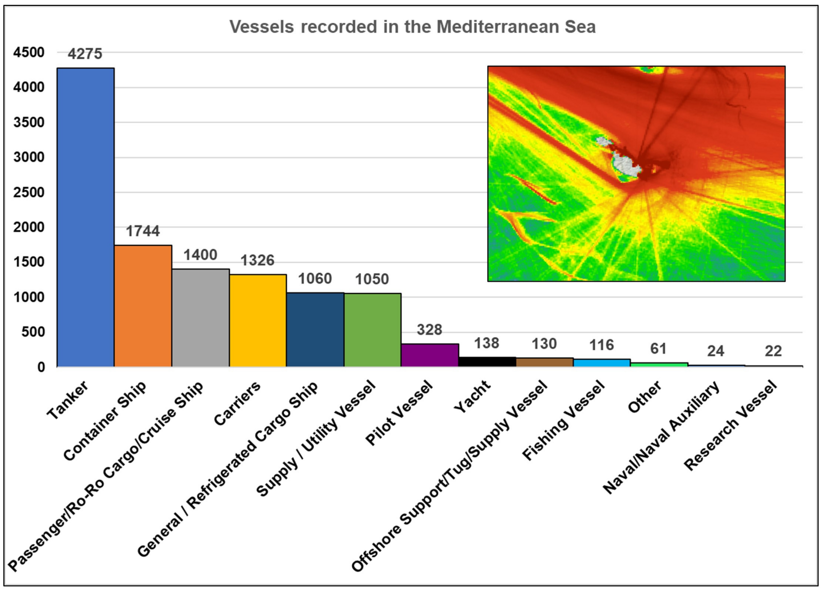

Figure 5: Vessels within the Maltese Ports. Source data (Transport Malta, 2023).

showed a decrease in the number of "ON"/"OFF" Proton Exchange Membrane (PEM) electrolyser cycles for increasing magnitude of the FLASC ESS capacity in all equipment combinations investigated where the FLASC HPES system was integrated, as well as an increase in hydrogen production for equipment combinations with an integrated FLASC HPES system with a capacity range of 20 MWh and higher. In addition, the curtailed energy not available for use in the H_2 production process due to limitations imposed by the technical characteristics of the equipment used, fell to below 10 per cent of the total curtailed energy.

3.2 Candidate Site Identification Results

The decision matrix was considered for both the 'Linear' and the 'Rectangular' WT arrays, as shown in Figure 5. The criteria considered and the rankings given for each location can be seen in the decision matrix seen in Table 4.

From the ensuing results, it was possible to shortlist the more attractive locations for the proposed HydroGenEration project concept. The score for each criterion was assigned based on the possible benefits that the candidate location could provide to the different technical components of the HydroGenEration project concept. The scores were assigned following in-depth discussions within the HGE team and using a decision matrix approach.

The results were ranked as shown in Table 5, from the highest to the lowest scores. The difference between the assigned scores is primarily due to the effect of the footprint of the arrays. The length of obstruction presented by the linear array is longer than that of the rectangular array. Therefore, in order to maintain the required safety distance from the wind farm, vessels would need to take a longer detour for a linear array, whilst the detour for a rectangular array would be shorter. This also results in a larger no anchorage zone being present in the linear array, which may also hinder the installation of pipelines and subsea cables. The most favourable location was found to be Site 2E, followed by Site 1B (see Figure 3).

Once the site selection process had been completed, online webinars were held with local stakeholders in order to get feedback on the locations identified by the HGE team for such a hypothetical concept. The sites selected raised no particular concerns, although one must also mention that in reality such a process would require a much more in-depth analysis based on scientific research and involving as many stakeholders as possible.

These results were also shown to be in line with national policies, specifically with the 2023: "National Policy for the Deployment of Offshore Renewable Energy", a policy that was drafted by the Energy and Water Agency and which was issued for public consultation after the current research project work was carried out (Energy and Water Agency & Ministry for the Energy, Environment and Regeneration of the Grand Harbour, 2023). This national report highlights those areas within the EEZ where RE projects could be implemented. In addition to this, the national report further highlights the criteria which need to be considered for such RE projects, most if not all of which were also taken into consideration in the shown Decision Matrix.

Factor	Linear Array 1A	1B	1C	1D	1E	1F	Rectangular Array 2A	2B	2C	2D	2E	2F
Environmental Activities												
Location with respect to EEZs	1	3	1	3	4	3	1	3	1	3	4	3
Vicinity to Natura2000 sites	4	4	3	4	4	4	4	4	3	4	4	4
Bird Rafting Sites in the Central Mediterranean	2	4	4	4	4	4	2	4	4	4	4	4
Maritime and Related Activities												
Distance from Harbor/port	1	3	4	4	3	2	1	3	4	4	3	2
Harbour Approach Routes	4	2	1	1	4	4	4	1	2	2	4	4
Land reclamation off the coast of Xghajra	4	4	4	4	4	4	4	4	4	4	4	4
Spoil Grounds	4	4	4	4	4	4	4	4	4	4	4	4
Proximity to ship bunkering Site	3	1	2	2	1	2	3	1	2	2	4	2
Subsea telecommunication cables	2	3	2	3	2	4	2	3	2	3	3	4
Proposed LNG pipeline	4	4	2	4	4	4	4	4	2	4	4	4
Existing and Proposed Interconnector	2	4	4	4	4	4	2	4	4	4	4	4
Inter-island travel	4	4	4	4	4	4	4	4	4	4	4	4
Military Activities	4	4	3	4	4	4	4	4	3	4	4	4
Interaction with Aviation	4	4	1	1	4	4	4	4	1	1	4	4
Leisure aquatic activities (diving)	2	4	3	4	4	4	2	4	3	4	4	4
Fishing, Fish Farming and aquaculture activities	1	4	1	1	1	4	1	4	1	1	1	4
Technical and Metocean Conditions												
Prevalent Wind direction	4	4	3	3	3	2	3	3	2	2	2	1
Wind speed	4	4	4	4	4	3	3	3	3	3	3	2
Wave height	3	3	4	3	1	1	3	3	4	3	1	1
Sea depth	2	2	2	2	3	2	2	2	2	2	3	2
Visual impact	1	4	2	4	4	4	1	4	2	4	4	4
Mooring Lines	2	2	2	2	4	3	2	2	2	2	4	3
No. of turbines	4	4	4	4	4	4	4	4	4	4	4	4
Total	**64**	**75**	**60**	**69**	**74**	**74**	**62**	**72**	**59**	**68**	**76**	**72**

Table 4: Decision Matrix used for shortlisting the candidate offshore sites for the HydroGenEration project concept based on the weighting factors presented in Table 2.

Location / Site No.	Score	Location / Site No.	Score
2E	76	2D	68
1B	75	1A	64
1E/1F	74	2A	62
2F/2B	72	1C	60
1D	69	2C	59

Table 5: Results of the Decision Matrix.

3.3 Potential Hydrogen End Users

The use of hydrogen as a fuel for air and marine transport has great potential, as these sectors today cannot be directly electrified and need a physical fuel for their motive power. Hydrogen and ammonia can effectively compete with fuels derived from petroleum. In particular, unconverted hydrogen is well positioned to become a key element for use in short sea voyages, and when converted to methanol or ammonia, can serve as a fuel used by international shipping. The possibility of incorporating the use of hydrogen for marine transport in Malta was investigated in earlier work (Moise, 2021).

Work conducted as part of project HydroGenEration highlighted Malta's favourable location on the busy sea routes across the Mediterranean Sea. This strategic position is well placed to further develop and consolidate the various maritime activities and strengthen Malta as a Mediterranean hub. Already today, Malta's territorial waters have bunkering areas, which enable for the entry and safe anchorage of various vessels. The number and types of vessels that visit Maltese Ports in 2023 can be seen in Figure 5.

For this reason, the development and establishment of an offshore hydrogen production plant can bring with it additional benefits to the Maltese Islands. This is due to the possibility of easy access both for marine vessels that will utilise compressed hydrogen as propulsion fuel in the future and, more realistically, in the near future for marine H_2 carriers to collect the hydrogen being produced offshore and transporting it to other locations for storage and further consumption.

The results of the numerical modelling showed that the volume of offshore hydrogen produced by means of a wind power plant consisting of ten, 10 MW wind turbines with an integrated FLASC ESS, could generate enough H_2 to refill the cargo tanks of approximately 60 hydrogen seagoing carriers (see Table 6) in a year (based on actual wind conditions for 2016).

This means that each vessel will carry to the end-users approximately 70 tons of hydrogen. The quantity of wind-generated electricity required to fill a single H_2 carrier is equivalent to 4,415 MWh. This means that at each refuelling, the H_2 carrier would load about 2% of the total annual hydrogen production from the HydroGenEration project concept in a Central Mediterranean wind climate scenario.

Month	Total Number of H_2 Carrier Offloads
Jan.	6
Feb.	7
Mar.	7
Apr.	7
May	6
Jun.	3
Jul.	3
Aug.	3
Sep.	4
Oct.	4
Nov.	6
Dec.	6
Annual	62

Table 6: Table showing the number of hydrogen carriers which would have been supplied by the HydroGenEration project concept on a monthly basis for the base year 2016.

Not all sectors of the economy can be electrified in the near or foreseeable future, so many technologies will need fuel in the form of raw materials, rather than in the form of clean energy for a long time to come. Examples of these technologies are seagoing vessels used in international shipping, long-range aircraft used in aviation, steel production, and seasonal energy storage technologies which cannot be electrified directly. So, clean, renewable electricity cannot be used in such applications. The solution to this problem may lie in converting electricity, especially that derived from renewable sources, into other physical forms, i.e., turning it into gaseous and liquid carriers. In addition to meeting the physical fuel needs of some industries, such conversion would improve the transport of energy over long distances and minimise transport losses. Hydrogen can act as such an energy carrier in its gaseous, liquid and converted forms. The application of such technologies suggests that the use of hydrogen in various aggregate states will help to meet about 12% of the electricity demand from end-users and also reduce CO_2 emissions by 10% (OECD, 2022). By incorporating carbon capture and storage technologies into this scenario, it is possible to significantly reduce the CO_2 content in the atmosphere, which in the long term should lead to a zero-emission system (Food and Agriculture Organization of the United Nations, 2022).

4 Conclusions

This research highlights Malta's favourable location on the busy sea routes across the Mediterranean Sea. This strategic position has all the prerequisites for the further development and consolidation of various maritime activities and for Malta to reinforce itself as a Mediterranean hub.

The numerical modelling showed that for three 10 MW wind turbines supplying a 24 MW electrolyser, there will be a marginal increase in the amount of H_2 of 0.3% when a 25 MWh FLASC system is interfaced between the intermittent supply and the H_2 production plant. More significantly, the number of electrolyser "ON"/"OFF" cycles decreased by 66% with integrated energy storage over the 12-month time frame under scrutiny.

Even today, Malta's territorial waters already host bunkering areas, creating the prerequisites for the entry and safe anchorage of various vessels. Ports and harbour infrastructure are also geared to support maritime activities. For this reason, the development and establishment of offshore hydrogen production could bring additional benefits to the Maltese islands. This is due to the possibility of easy access both for seafaring vessels that will, in the future, utilise the compressed hydrogen as a fuel for motive power and more realistically, in the nearer future for seagoing H_2 carriers to collect the hydrogen produced and to transport it elsewhere for storage and future consumption.

The work presented in this research report looks into the technical performance characteristics of an islanded decarbonised H_2 production plant and presents the selection process for candidate site/s suitable for the HydroGenEration project concept by taking into consideration the technical requirements, system interactions and dependence on a number of factors related to the environmental, maritime and energy activities underway in the vicinity of the Maltese Islands.

The results of this work show that the ideal candidate site would be Site 2E, located on the East side of the islands and within Area 1 of Malta's EEZ. Preliminary calculations show that the volume of offshore hydrogen produced by means of the HydroGenEration project concept could generate enough H_2 to refuel about 60 hydrogen carriers based on 2016 wind data in a case study for Central Mediterranean wind conditions. It is important to keep in mind that this work formed part of a process to consolidate the HydroGenEration project concept for offshore, green hydrogen production using electrical energy stabilised by a FLASC ESS.

In conclusion, the HGE project includes a high-level techno-economic analysis to identify the costs of the overall system and to come up with a Levelised Cost of Hydrogen (LCOH) for the concept project, subject to local offshore conditions. Such findings are subject to future national policy adjustments and to further studies and surveys. Additional factors can also affect the results presented in this work.

Acknowledgements

The work presented in this Research Report was undertaken as part of project: "Hydro Pneumatic Energy Storage for Offshore Green Hydrogen Generation – HydroGenEration", financed by the Energy and Water Agency under Malta's National Energy and Water Research and Innovation Strategy (2021-2030) — Grant Agreement Ref.: EWA 64/22.

The WIND4H2 project was supported through the Maritime Seed Award (MarSA) 2019, a joint initiative between Transport Malta (formerly Malta Marittima) and the University of Malta supported by the TAKEOFF Business Incubator, Knowledge Transfer Office and the Centre for Entrepreneurship and Business Incubation (CEBI) at the University of Malta.

The Light Detection and Ranging (LiDAR) system was purchased through the European Regional Development Fund for the setting up of a Solar Laboratory (ERDF 335), part-financed by the European Union.

The authors also acknowledge the help and support of Din L-Art Ħelwa – National Trust of Malta, for hosting the LiDAR wind measurement equipment at the Qalet Marku Tower, Baħar iċ-Ċagħaq, Malta.

References

Ahmed, A., Pompodakis, E. E., Katsigiannis, Y., & Karapidakis, E. S. (2024). Optimizing the installation of a centralized green hydrogen production facility in the island of Crete, Greece. *Energies*, *17*(8), 1924.

Alessandro, F., & Giovannini, C. (2023). Recent and future advances in water electrolysis for green hydrogen generation: Critical analysis and perspectives. *Sustainability*, *15*(24), 16917–16917.

Aquaventus. (2024). Aquaventus, the green energy revolution starts in the North Sea [Accessible at https://aquaventus.org (Retrieved October 18, 2024)].

Borg, A., Sant, T., Buhagiar, D., Cutajar, C., & Farrugia, R. N. (2023a). Numerical modelling of a hydro-pneumatic energy storage system for smoothing power fluctuations from offshore wind. *Journal of Physics: Conference Series*, *2626*(1), 012014–012014.

Borg, A., Sant, T., Buhagiar, D., Farrugia, R. N., & Micallef, C. (2023b). A numerical model comparison of the energy conversion process for an offshore hydro-pneumatic energy storage system. *Applied Sciences*, *13*(12), 7189–7189.

Buhagiar, D., & Sant, T. (2017). Modelling of a novel hydro-pneumatic accumulator for large-scale offshore energy storage applications. *Journal of Energy Storage*, *14*(2), 283–294.

Continental Shelf Department. (2022). Preliminary market consultation — for the proposal of economic activities within Malta's exclusive economic zone [Accessible at https://www.etenders.gov.mt (Retrieved December 4, 2023)].

Cordina, C., Farrugia, R., & Sant, T. (2017). Wind profiling using LiDAR at a coastal location on the Mediterranean island of Malta [Bari, Italy]. *9th European Seminar OWEMES*.

Cradden, L., Kalogeri, C., Barrios Martinez, I., Galanis, G., Ingram, D., & Kallos, G. (2016). Multi-criteria site selection for offshore renewable energy platforms. *Journal of Renewable Energy*, *87*, 790–806.

Cutajar, C., Sant, T., Farrugia, R. N., & Buhagiar, D. (2021). A software tool for the design and operational analysis of pressure vessels used in offshore hydro-pneumatic energy storage. *Journal of Energy Storage*, *40*, 102750.

Danish Energy Agency. (2023). Denmark's energy islands [Accessible at https://ens.dk (Retrieved February 11th, 2025)].

Davis, N. N., Badger, J., Hahmann, A. N., Hansen, B. O., Mortensen, N. G., Kelly, M., Larsén, X. G., Olsen, B. T., Floors, R., Lizcano Casso, G., Lacave, O., Bosch, A., Bauwens, I., Knight, O. J., Potter van Loon, A., Fox, R., Parvanyan, T., Krohn Hansen, B. O., Heathfield, D., & Drummond, R. (2023). The global wind atlas: A high-resolution dataset of climatologies and associated web-based application. *Bulletin of the American Meteorological Society*, *104*(8), E1507–E1525.

Diaz, H., Fonesca, R. B., & Guedes Soares, C. (2018). Site selection process for floating offshore wind farms in Madeira islands. In *Advances in renewable energies offshore*. Taylor & Francis.

DNV. (2015). A new era for hydrogen energy unveiled by summer students at DNV GL [Accessible at https://www.dnv.com (Retrieved October 18, 2024)].

Dolphyn Hydrogen. (2024). Producing ultra low carbon hydrogen economically and at scale [Accessible at https://www.dolphynhydrogen.com (Retrieved October 18, 2024)].

Drago, A. (2006). *WERMED Malta page* [Accessible at http://www.capemalta.net (Retrieved October 2023)].

Energy and Water Agency & Ministry for the Energy, Environment and Regeneration of the Grand Harbour. (2023). National policy for the deployment of offshore renewable energy [Accessible at https://energywateragency.gov.mt].

Environment and Resources Authority. (2013). Physical features [Accessible at https://era.org.mt].

Environment and Resources Authority. (2023). Meps geoportal [Accessible at https://meps.eraportal.org.mt (Retrieved October 22, 2023)].

European Marine Observation and Data Network. (n.d.). Annual maritime route density [Accessible at https://emodnet.ec.europa.eu (Retrieved December 4, 2023)].

Foglini, F., Prampolini, M., Micallef, A., Angeletti, L., Vandelli, V., Deidun, A., & Taviani, M. (2015). Late quaternary coastal landscape morphology and evolution of the Maltese islands (Mediterranean sea) reconstructed from high-resolution seafloor data. *Geological Society, London, Special Publications*, *411*(1), 77–95.

Food and Agriculture Organization of the United Nations. (2022). The state of Mediterranean and Black Sea fisheries [Accessible at https://www.fao.org].

Galdies, C. (2022). The state of the climate 2022 - a multidecadal report and assessment of Malta's climate [Accessible at https://www.um.edu.mt].

Gao, F. Y., Yu, P. C., & Gao, M. R. (2022). Seawater electrolysis technologies for green hydrogen production: Challenges and opportunities. *Current Opinion in Chemical Engineering*, *36*, 100827.

Grech, K. (2022). An exclusive economic zone for Malta [Accessible at https://mmf.org.mt (Retrieved October 2023)].

Honsho, Y., Nagayama, M., Matsuda, J., Ito, K., Sasaki, K., & Hayashi, A. (2023). Durability of PEM water electrolyzer against wind power voltage fluctuation. *Journal of Power Sources*, *564*, 232826–232826.

IEA. (2020). NREL turbine-models power curve [Accessible at https://nrel.github.io (Retrieved October 2023)].

IMO. (2021). IMO 2020 fuel oil sulphur limit - cleaner air, healthier planet [Accessible at https://www.imo.org (Retrieved October 4, 2023)].

IMO. (2023). IMO's work to cut ghg emissions from ships [Accessible at https://www.imo.org (Retrieved September 2023)].

Kojima, H., Nagasawa, K., Todoroki, N., Ito, Y., Matsui, T., & Nakajima, R. (2023). Influence of renewable energy power fluctuations on water electrolysis for green hydrogen production. *International Journal of Hydrogen Energy*, *48*(12), 4572–4593.

Lhyfe. (2023). Lhyfe announces that Sealhyfe, the world's first offshore hydrogen production pilot, produces its first kilos of green hydrogen in the Atlantic Ocean [Accessible at https://www.lhyfe.com (Retrieved October 18th, 2024)].

Micallef, A., Foglini, F., Le Bas, T., Angeletti, L., Maselli, V., Pasuto, A., & Taviani, M. (2013). The submerged paleolandscape of the Maltese islands: Morphology, evolution and relation to quaternary environmental change. *Marine Geology*, *335*, 129–147.

Moise, T. (2021). *Techno-economic feasibility of floating offshore wind-driven hydrogen production for decarbonising maritime transport between Malta and Gozo* [Master's thesis, M.Sc. in Sustainable Energy, University of Malta].

MUSICA. (2024). Multiple use of space for island clean autonomy [Accesible at https://musica-project.eu (Retrieved October 18th, 2024)].

National Statistics Office. (2022a). The state of the climate 2022: A multidecadal report and assessment of Malta's climate [Accesible at https://nso.gov.mt (Retrieved Februar 13th, 2023)].

National Statistics Office. (2022b). Transport statistics 2021 [Accesible at https://nso.gov.mt (Retrieved October 4, 2023)].

OECD. (2022). OECD tourism trends and policies 2020 [Accesible at https://www.oecd.org (Retrieved October 2023)].

Plan Bleu. (2021). Maritime transport in the Mediterranean [Accesible at https://planbleu.org (Retrieved October 2023)].

Planning Authority. (2016). Harbour approach routes [Accesible at https://testsdi.gov.mt (Retrieved October 21st, 2023)].

Settino, J., Farrugia, R. N., Buhagiar, D., & Sant, T. (2022). Offshore wind-to-hydrogen production plant integrated with an innovative hydro-pneumatic energy storage device. *Journal of Physics: Conference Series*, *2151*(1), 012013.

Transport Malta. (2013). Malta significant wave height study [Accessible at https://www.transport.gov.mt (Retrieved October 2023)].

Transport Malta. (2023). Maritime statistics - Transport Malta [Accessible at https://www.transport.gov.mt (Retrieved April 2023)].

Transport Malta. Malta bunkering areas [Accessible at https://www.transport.gov.mt (Retrieved October 20th, 2023)].

Weiß, A., Siebel, A., Bernt, M., Shen, T.-H., Tileli, V., & Gasteiger, H. A. (2019). Impact of intermittent operation on lifetime and performance of a PEM water electrolyzer. *Journal of the Electrochemical Society*, *166*(8), F487–F497.

Zaini, A. A., Hannan, M. A., Al-Shetwi, A. Q., Begum, R. A., Hossain, M. J., Ker, P. J., & Indra, M. (2023). Hydrogen electrolyser technologies and their modelling for sustainable energy production: A comprehensive review and suggestions. *International Journal of Hydrogen Energy*, *48*(72).