Interreg Atlantic Area

Co-funded by the European Union

H2YDEA

Boosting the hydrogen transition in the Atlantic Area ports

Deliverable D 4.3.1

Identification of bottlenecks and possible measures

DISCLAIMER

DOCUMENT INFORMATION

GRANT AGREEMENT NUMBER	EAPA_0057/2022
PROJECT ACRONYM	HYDEA
WORK PACKAGE	WP4
RELATED ACTIVITY	ACT3
DELIVERABLE REFERENCE	D4.3.1
TITLE	Identification of bottlenecks and possible measures
STATUS	Final version
AUTHOR(S)	UPORTO, Port of Brest, Port of Seville, FEM and APVIGO
DELIVERY LEAD	UPORTO
FILE NAME	D4.3.1_vf

DOCUMENT HISTORY

VERSION	DATE	DESCRIPTION	REVIEWER
0.0	14/05/2024	Initial outline	UPORTO
1.0	23/05/2024	Updated initial outline	UPORTO
1.1	12/06/2024	Detailed workload distribution	UPORTO
1.2	25/06/2024	Detailed chapter guidelines	ALL
1.3	08/07/2024	Contribution with sub-chapter 2.1	BrestPort
1.4	10/07/2024	Contribution with chapter 2	Port of Seville
1.5	10/09/2024	Contribution with chapter 2	FEM and APVIGO
1.6	10/10/2024	Compilation of latest contributions	UPORTO
1.7	27/11/2024	Final compilation of contributions	UPORTO

EXECUTIVE SUMMARY

This deliverable summarizes the critical bottlenecks and considerations to enable the implementation of hydrogen-based infrastructures in ports in each participating region. It involves the identification of the considerations at different levels (technical, economic, social, regulatory). The information is based on literature review, expert knowledge from the partners and external experts, and the previous findings of this project.

This activity consists of identifying the technical, economic, social and legal challenges and barriers for implementation of hydrogen-based infrastructures in the ports of each participating region. It is known that the main barriers that prevent the deployment of renewable H_2 are the cost of its generation, this being a purely technical aspect and that it depends on the advances made by the scientific community to control the electrolysis processes, there are also technical limitations in H_2 transformation into a raw material/energy vector suitable for final uses and its integration into the industrial processes of consumers. Also, a lack of an existing clean H_2 value chain represents one of the main obstacles to overcome for the development of a low carbon H_2 economy. Finally, the need for international H_2 standards and regulations represents a major obstacle to the development of a global H_2 market.

This work consists of the analysis of documents published by the main associations linked to H_2 sector, as well as strategic research agendas, white books, and roadmaps worldwide, since it is known that the same barriers affect all territories equally, whether they are or not from the Atlantic Area.

As there is no specific association, technology platform or cluster for the advancement of H_2 in ports, the documents of relevant associations where renewable energies, transport (naval, land and rail), logistics, or H_2 are represented were analyzed. Relevant associations include: European Clean Hydrogen Alliance, WATERBORNE TP, WindEurope, Processes4Planet Research Association, among others.

UPORTO lead this work of identifying both barriers and solutions. At first, it revolved around a general level, then, based on this result, UPORTO pointed out which are the barriers that specifically affect the ports of the Atlantic Area and which are the equally specific solutions for these territories. Hence, both the technological partners and the ports participating in the HYDEA project partook in the writing and review process. To increase the quality of the results of the analysis, these results were validated with primary data from external experts. These experts were invited from the HYDEA community.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

AA	Atlantic Area
AAPs	Atlantic Area Ports
ADR	Dangerous Goods by Road
AEM	Anion Exchange Membrane
AFIR	Alternative Fuels Infrastructure Regulation
APA	Portuguese Environmental Agency
APREN	Portuguese Renewable Energy Association
CAP	Climate Action Plan
CCS	Carbon Capture and Storage
CMSM	Carbon Molecular Sieve Membranes
CNMC	National Commission for Markets and Competition
DGAMPA	Direction Générale des Affaires Maritimes, de la Pêche et de l'Aquaculture
DGEG	Directorate-General for Energy and Geology
DGRM	Directorate-General for Natural Resources, Safety and Maritime Services
DMAP	Designated Maritime Area Plan
EERE	Energy Efficiency and Renewable Energy
EIA	Environmental Impact Assessment
EN-H2	National Strategy for Hydrogen
EU	European Union
FCEVs	Fuel cell electric vehicles
FID	Final Investment Decision
GHG	Greenhouse Gases
HB	Haber-Bosch
HDVs	Heavy-Duty Vehicles
HPAs	Hydrogen Purchase Agreements
HRS	Hydrogen Refueling Stations
HTO	Hydrogen-To-Oxygen
ICPE	Installation Classée Pour l'Environnement
IEA	International Energy Agency
LCoE	Levelized Cost of Energy
LH_2	Liquid Hydrogen
LNEG	National Laboratory of Energy and Geology
LOHC	Liquid Organic Hydrogen Carriers
MACs	Maritime Area Consents
MAP	Maritime Area Planning
MARA	Maritime Area Regulatory Authority
MRE	Marine Renewable Energy
MRES	Marine Renewable Energy Sources
NDP	National Development Plan
NHS	National Hydrogen Strategy
OIES	Oxford Institute for Energy Studies
ORE	Offshore Renewable Energy
PAER	Renewable Energy Allocation Plan
PEM	Proton Exchange Membrane
PNEC	National Plan of Energy and Climate
PPRT	Plan de Prévention des risques technologiques
PRR	Recovery and Resilience Plan
PSOEM	Maritime Spatial Planning Situation Plan

PTO	Power Take-Off
RES	Renewable Energy Sources
RFNBO	Renewable Fuels of Non-Biological Origin
SEAI	Sustainable Energy Authority of Ireland
SET	Strategic Energy Technology
SI	Statutory Instruments
SNH	Stratégie Nationale Hydrogène
SNP	Stratégie Nationale Portuaire
SOEC	Solid Oxide Electrolysis Cells
TMD	Transport de Matière Dangereuse
TEN-T	Trans-European Transport Network
WEC	Wave Energy Converter
ZIBAC	Zones Industrielles Bas Carbone
CO_2	Carbon dioxide
H_2	Hydrogen

1 Introduction

Europe has established itself as a leader in the global shift towards renewable energy, propelled by ambitious climate objectives and a dedication to reducing carbon emissions. The European Union (EU) is striving for climate neutrality by 2050, with a pivotal focus on renewable energy in this transition. In the last 10 years, the continent has achieved notable advancements in the implementation of wind, solar, and hydroelectric energy sources. The European Green Deal, launched in 2019, emphasizes the EU's commitment to establishing a sustainable economy, pointing out the necessity for increased investments in clean energy technologies, energy efficiency, and the upgrading of energy infrastructure. With the gradual reduction of fossil fuels, Europe continues to explore new innovations, among which hydrogen stands out as particularly promising.

Hydrogen is increasingly recognized as a significant component in Europe's evolving energy landscape, among the diverse array of renewable energy solutions. Hydrogen, especially green hydrogen generated via electrolysis with renewable energy sources, holds the promise to transform sectors that are challenging to electrify, including steel manufacturing, heavy transportation, and aviation. Hydrogen serves as a clean energy carrier, offering energy security and facilitating the integration of renewables into the grid. European nations are making significant investments in hydrogen initiatives, which may establish hydrogen as a fundamental component of a decarbonized economy, connecting renewable energy generation with energy use across various sectors.

The Atlantic Area Ports are increasingly recognized as pivotal sites for advancing hydrogen infrastructure development. The strategic location of these ports makes them well-suited to serve as centres for hydrogen production and distribution, especially given their proximity to renewable energy sources, notably offshore wind. Initiatives are currently in progress to set up green hydrogen production facilities in various European ports, including Rotterdam, Bilbao, Le Havre, Vigo, Galway, and Sines, with the objective of providing hydrogen for industrial applications and transportation. These ports function as essential hubs for hydrogen exports, linking Europe with various regions via shipping routes. The establishment of hydrogen refueling stations for both maritime and land-based transport is regarded as a crucial advancement in the effort to decarbonize the shipping sector. Nonetheless, expanding these initiatives necessitates cooperation among governmental bodies, private entities, and global partners to establish a thorough hydrogen supply chain.

Despite its potential, green hydrogen encounters several significant challenges. The current performance of electrolyzers and hydrogen storage techniques is suboptimal, resulting in elevated costs and hindering widespread implementation. Moreover, the generation of hydrogen demands substantial quantities of renewable electricity, which calls for significant increases in wind, wave and solar energy capacity. Public acceptance poses a significant challenge, as there are prevalent concerns regarding safety and a general lack of understanding about the advantages of hydrogen. From an economic perspective, green hydrogen remains considerably more costly than fossil-based hydrogen, necessitating substantial investments in infrastructure for its distribution and storage. Finally, the legal frameworks surrounding hydrogen production, transport, and use are still in their infancy, resulting in uncertainties for investors and project developers. Overcoming these challenges will be essential for realizing hydrogen's complete potential in the shift toward renewable energy.

The primary aim of this deliverable is to identify and outline the essential bottlenecks and mitigation measures necessary for facilitating the implementation of hydrogen-based infrastructures in ports across each participating region. The process entails the identification of the considerations at different levels, including technical, economic, social, and regulatory aspects. Suggested strategies for addressing the identified barriers and challenges are also included.

This chapter serves as an introduction, providing a general overview of the current landscape of energy transition, with a particular focus on hydrogen. The second chapter, comprising four sub-sections, delves into the technical, economic, social, and legal challenges and barriers associated with hydrogen, following the implementation of hydrogen-based infrastructures in ports. The subsequent chapter outlines the mitigation measures and solutions designed to tackle the challenges and barriers discussed in the preceding chapter. Finally, the conclusion provides a comprehensive summary of the findings presented in this document.

1.1 Technical Challenges and Barriers

1.1.1 Marine Renewable Energy

From a technical perspective, the availability of green hydrogen, which relies on renewable energy sources (RES), is a critical factor. Electrolysis, which uses renewable energy to split water into hydrogen and oxygen, is a common method for hydrogen production. This process requires significant energy input and efficient electrolyzers. Currently, the majority of hydrogen production is achieved through the employment of fossil fuels – about 96% –, as is the case with the prevailing steam reforming process with natural gas. Electrolysis currently accounts for the remaining percentage, according to [1]. To tackle this matter, there needs to be a significant uptake in RES production and installed capacity. However, this immediately prompts two important issues: i) contention with electrical grid needs between inshore/onshore activities, and ii) contention for space to allocate RES technologies (*e.g.*, land area for solar photovoltaic and wind). Seaports are equally affected by these barriers, given their own energy needs for infrastructure and operations, and the limited available space for installing RES and auxiliary systems within the port area. It also creates a direct dependency upon the mainland electrical grid, making seaports susceptible to fluctuating tariffs and external factors.

To promote energy autonomy and sustainability, marine renewable energy sources (MRES) can play a pivotal role. Three of the most promising sources – offshore wind, wave and tidal – exhibit an estimated global annual resource of 192 800 TWh, 32 000 TWh and 22 000 TWh, respectively [2]. Since 2010, Europe has installed 30.5 MW of tidal stream, with 11.75 MW being currently in water and 280 kW of which in 2023 alone. For wave energy, the corresponding values are 13.3 MW, 1 MW and 595 kW [3]. In 2023, AA regions contributed significantly towards these goals: France towards tidal, Portugal and Spain also towards wave. Regarding wind, there is a growing trend towards deeper waters (floating offshore wind), given the increasingly limited spatial availability closer to the shorelines and the greater resource density offshore, among other factors. In 2023, Europe installed 3.8 GW of offshore wind, with the AA region of France contributing with 360 MW. Considering the annual offshore wind power installation target of about 22 GW by 2030 [4], there will be a very strong pressure towards projecting, licensing, constructing and installing offshore wind turbines in the upcoming years. Furthermore, the

European Union's (EU) set "*targets for an installed capacity of at least 60 GW of offshore wind and 1 GW of ocean energy by 2030, and 300 GW and 40 GW, respectively, by 2050*" [5].
Considering this context, there is an uphill struggle for each of these high-potential MRES. Looking at the technical aspects [6–10]:

- ***Offshore wind***: this energy source has somewhat become a victim of its own success, recently. Offshore wind is more mature than tidal or wave energy, given the significant experience from onshore and bottom-fixed nearshore wind technologies. Even so, offshore wind still requires some technological standardization to achieve the same degree of maturity. Several pioneering projects, such as Portugal's 25 MW WindFloat Atlantic [11], have even achieved great success in their initial deployment and operation stages. However, this success has prompted the announcement of large projects (*e.g.*, Portugal's auction of 10 GW by 2030, recently reduced to 1 GW) whose feasibility and requirements are challenging. The aforementioned targets will require i) installed capacity to meet not only hydrogen production targets, but also mainland and seaport internal consumptions (*i.e.*, usage competition), ii) proximity to seaports, in order to ensure viable transportation, installation, operation and maintenance procedures throughout the life-cycle, as well as access to electricity connections to the mainland, iii) space allocation for companies and industrial entities within the seaport area to manufacture, test, repair, store and (un)load the necessary offshore wind equipment (particularly the turbine components), iv) uptake and/or import of critical materials and components to produce and install the turbines and auxiliary equipment (*e.g.*, mooring lines, platforms and generators), which will further strain European production and the already significant dependency of external suppliers, v) investment in supporting equipment and personnel to handle the life-cycle stages of offshore wind turbines (*e.g.*, tug boats, adapted vessels, AUVs, and skilled divers and operators), vi) developing, testing, validating and monitoring offshore wind systems throughout extreme events, such as storms and large wave loads/wind gusts, to ensure survivability at sea and optimal availability; vii) establish electricity conversion and transfer means throughout the offshore wind farms and to the seaport (*e.g.*, sub-stations and submerged power cables), viii) define the model of energy-to-hydrogen conversion (*i.e.*, local production of H_2 and transport to the seaport, or electricity transfer to the seaport for conversion into H_2 in onshore installations), ix) competition with other seaport activities (*e.g.*, shipping, maritime traffic routes, and dedicated terminals) for space and supporting vessel/equipment access, to which adds collision risks, x) an offset between the available number, dimension and capability of companies and industrial partners working in offshore wind, and the targets/requirements setup for the upcoming years, xi) electrolyzer performance with power fluctuations from offshore wind, and xii) technological standardization and typology availability for offshore wind turbines: according to [7], "in *the last 20 years they have nearly quadrupled in height – from around 70 m to 260 m – almost three times taller than the Statue of Liberty in New York. Rotor diameters have increased fivefold in the past 30 years. Wind turbines with capacities of 8 or 9 MW are common, but newer models reach 14 to 18 MW*";
- ***Wave energy***: to the constraints highlighted for offshore wind, wave energy is expected to face barriers inherent to its lower technological maturity condition. Hundreds of different concepts exist worldwide, spread across distinct typologies: attenuator, oscillating water column, oscillating wave surge converter, wave overtopping, rotating mass, point absorber, terminator, etc. Furthermore, each wave energy converter (WEC) is generally developed for a specific region

with specific wave climates (*e.g.*, mild Mediterranean Sea versus the high-energy intensity of the North Atlantic Ocean) and operational depths (*e.g.*, onshore, nearshore and offshore). To these add alternative approaches to mooring line design (*e.g.*, catenary and tension-leg platform, among others), Power Take-Off (PTO) generator (*e.g.*, hydraulic, direct drive electric, piezoelectric, among others), and several other divergence sources [12–14]. As such, it has been extensively difficult to achieve commercial standardization, investment channeling and economies of scale within the wave energy sector. To this adds the particularly challenging environment at sea, including large wave loads, the risk of water infiltration and hull breach, biofouling and corrosion/exposure of sensitive electromechanical equipment. Also, while offshore wind has reached installed capacities of multi-MW per unit, wave energy devices generally bolster 1 MW or less capacity per device (with punctual exceptions, as the Wave Dragon and some onshore WECs). This will imply significant efforts towards upscaling and/or an investment in a larger number of units, which may occupy a significantly larger area of marine space (thus conflicting with other uses/restrictions). While there are several recent devices that hold promise, such as CorPower's point absorber [15] or the Mutriku OWC [16], there have been important project shutdowns, from the Pelamis [17] to the Wello Oy Penguin [18], in no small part attributed to one or more of the aforementioned challenges. Therefore, there is equally a limited amount of data from sea trials, which restricts technological gains from learning curves and knowledge sharing across the sector, as a whole. Hence, most R&D efforts remain within the fields of reduced-scale experimental and numerical modelling. On this matter, it is also worth noting that there is still a significant degree of uncertainties related to various sub-topics of wave energy (*e.g.*, resource assessment and variability, PTO optimization and co-design, device efficiency, WEC farm layout and design standardization, among others), despite the increasing expertise and knowledge gathered by researchers over the past decades;

- ***Tidal energy***: with wide shallow shelf seas and a coastline with many straits and inlets, the northern part of the European Atlantic Arc offers extreme tidal ranges, and is endowed with technical tidal resource estimated to reach up to 5 GW, one of the world's best [19]. Tidal barrage is a mature and competitive technology that has been operating for almost 60 years in France [20], but concerns over their ecosystem impacts make it unlikely that it will be continued further along the Atlantic Arc. The main technological developments today are focussing on the free-standing tidal turbines (tidal stream technology), both with horizontal and vertical axis concepts. Tidal stream technology deployment in Europe is still limited, with 11.75 MW currently in the water and 30.5 MW of cumulated deployment since 2010 [3], excluding tidal barrage. The tidal energy sector ambitions to make great steps toward industrialisation in the next five years, with project pipeline of 137 MW publicly supported via EU programmes or national schemes, which supports their attractivity for private financiers. Specifically for France, the 17.5 MW FloWatt project slated to be deployed in Normandy will mark a turning point for the French tidal sector. The current ambition is to get pre-commercial farms ready and make tidal energy nearly competitive within a decade.

  One specificity of the tidal stream resource against other renewable energies (wind, wave, solar) is its excellent predictability; the tidal periodic oscillations and corresponding currents can be precisely anticipated. On the other hand, the resource in the European Atlantic Arc is concentrated in very peculiar, possibly isolated (away from the grid, around islands), areas near

Brittany and around the Republic of Ireland. Both the aforementioned specificities and high production costs, make the electricity production from tidal turbines rather be seen as a niche solution, suitable for base load (with complementary power production capability) or coupling with storage capabilities such as hydrogen, to feed isolated areas. Besides, the Iberic Peninsula offers virtually no tidal energy potential. Considering the specificities of the technology, the electricity from tidal turbines is not expected to compare with that of (offshore) wind or solar.

1.1.2 Energy Carriers

The implementation of hydrogen in ports involves several technical considerations. Hydrogen can be used as a clean fuel for various port operations, including powering ships, vehicles, and port equipment. This requires the establishment of hydrogen production, storage, and distribution infrastructure. Hydrogen storage solutions, such as compressed gas tanks or liquid hydrogen tanks, pose challenges due to the extremely low temperatures and high pressures required, necessitating robust safety measures and adequate space. Even so, hydrogen and hydrogen-derived energy carriers have the potential to bridge sectors with energy surpluses and those with energy deficits, reducing energy waste and promoting a more efficient energy use [21].

To take full advantage of this potential, it is crucial to examine the technologies used for hydrogen production, as well as the carriers derived from it (*e.g.,* ammonia and methanol). Green H_2 is typically produced in electrolyzers, which come in various types, such as conventional alkaline electrolyzers, anion exchange membrane (AEM) electrolyzers, proton exchange membrane (PEM) electrolyzers, and solid oxide electrolysis cells (SOEC).

Alkaline electrolysis, historically used to generate H_2 from hydropower [22], stands out as the most practical technology as it does not rely on critical raw materials for its manufacture. However, adapting this type of electrolyzer to operate using intermittent energy sources presents significant challenges, particularly during periods of low energy supply. At low current densities, the rate of oxygen production falls below the rate of hydrogen crossover through the diaphragm, which increases the hydrogen-to-oxygen ratio (HTO). HTO values of 4% or higher are considered explosive, and an emergency shutdown must be initiated at 2%. Additionally, an alarm should be triggered at 1.6% to provide a warning. Another limitation of the alkaline electrolyzers is their size. To withstand the highly basic nature of the electrolytes and maintain the structural integrity required to prevent contact between H_2 and O_2, the membranes (diaphragms) are typically thick. This thickness is responsible for a high ohmic resistance, and consequently, lower energy efficiency [23].

Different challenges arise for other types of electrolyzers. Proton exchange membrane (PEM) electrolyzers, for instance, rely on materials with low natural abundance on Earth, in direct conflict with the European Commission's [24]. Finding alternative materials that can resist the acidic and oxidative environments in this technology remains a significant challenge.

AEM electrolyzers and solid oxide electrolysis cells (SOEC) are two other types of electrolyzers. AEM electrolyzers perform alkaline electrolysis, but in contrast to the conventional setup which includes a diaphragm, it employs a membrane that is only permeate to anions (namely OH-). This membrane is thinner than the diaphragm of the conventional alkaline electrolyzer, thus reducing ohmic resistances. Membranes are also cheaper that the membranes of PEM [25]. SOECs operate at high temperatures, use steam water as a reactant and achieve very high efficiencies. Despite promising, both AEM and

SOEC technologies are still not widely employed in industry: AEM is still under development, to optimize features such as membrane stability and robustness [26], while SOEC technology still faces problems regarding long-term system durability [25]. Incremental progress may be a viable pathway to overcome the aforementioned problems, particularly those of the two most used types of electrolyzers (*i.e.*, PEM and conventional alkaline electrolyzers). In line with this, the Office of Energy Efficiency and Renewable Energy (EERE) has outlined short- and long-term goals for specific technical parameters of electrolyzers - Table 1 [27].

Table 1. Short- and long-term goals for key characteristics of electrolyzers set by EERE [27].

	2022 status	2026 targets	Ultimate targets
Alkaline Water Electrolyzer			
Stack performance	0.5 A/cm^2@ 1.9V/cell	1.0 A/cm^2@1.8 V/cell	2.0 A/cm^2@1.7V/cell
Stack electrical efficiency	51 kWh/kg H_2	48 kWh/kg H_2	45 kWh/Kg H_2
system energy efficiency	55 kWh/kg H_2	52 kWh/kg H_2	48 kWh/kg H_2
Stack average degradation rate	3.2 mV/kh	2.3 mV/kh	2.1 mV/kh
Stack lifetime	60 000 h	80 000 h	50 000 h
Proton Exchange Membrane Electrolyzer			
Total Platinum Group Metal content	3mg/cm^2	0.5 mg/cm^2	0.125 mg/cm^2
Stack performance	2.0 A/cm^2@1.9V/cell	3.0 A/cm^2@1.8V/cell	3.0A/cm^2@1.7V/cell
Stack electrical efficiency	51kWh/kg H_2	48 kWh/kg H_2	43 kWh/Kg H_2
system energy efficiency	55 kWh/kg H_2	51 kWh/kg H_2	46 kWh/kg H_2
Stack average degradation rate	4.8 mV/kh	2.3 mV/kh	2.0 mV/kh
Stack lifetime	40 000 h	80 000 h	80 000 h

Regardless of the type of electrolyzer, they all share a key feature inherent to electrolysis: the hydrogen production requires direct water consumption. Using potable water for this purpose would place a considerable load on water resources, making it an issue. Using seawater and purifying it with desalination technologies may be a solution [28].

The produced hydrogen is usually mixed with other species, namely oxygen and water, and needs to be further purified according to the desired degree of purity (depending on the applications envisaged). Technology has already been developed to accomplish this, consisting of a deoxidizer and a dehydrator [29].

Apart from production, H_2 presents challenges associated with its storage, as stated earlier. Due to its small molecular size, hydrogen can diffuse through storage containers, even those designed to store other gases properly. The same applies to pipelines.

H_2 also has low volumetric energy density, a problem that may be circumvented by converting it into liquid (hydrogen-derived) carriers. The most well-known carriers are methanol and ammonia, which present their own challenges.

Using methanol as an energy carrier involves several technical barriers that must be overcome before its widespread adoption, with production methods being among the most critical challenges. Currently, methanol is primarily produced from fossil fuel-derived syngas, a process that significantly contributes to CO_2 emissions, accounting for approximately 10 % of total emissions in the chemical and petrochemical sector. However, the development of more sustainable methanol production methods using CO_2 and green hydrogen can potentially revolutionize this process. This shift could facilitate a sustainable "methanol economy," where methanol serves as a viable alternative to fossil fuels for energy storage, transportation fuels, and raw material for various carbon-based products. Despite the potential benefits, significant advancements in producing methanol from CO_2 (direct CO_2 hydrogenation) are still required to realize this vision fully [30]. One significant challenge is the stability of the catalysts used in the direct CO_2 hydrogenation reaction. Usually, copper-based catalysts are employed for this reaction, which tends to deactivate in the presence of water or, at the very least, experience a loss of activity. Since water is an unavoidable by-product of this reaction, this presents a considerable limitation unless the water is continuously removed. Moreover, depending on the origin of the CO_2 used as a reactant, additional impurities may deactivate the catalysts. Another problem faced is that the conversion of CO_2 to methanol is usually limited to 15-25%. This low conversion rate not only impacts the economic viability of the process but also raises concerns about the overall energy balance and efficiency of utilizing CO_2 as a feedstock for methanol production [31].

Another significant concern is methanol's toxicity to humans, which poses health risks through ingestion, inhalation, or skin absorption. This requires stringent handling and storage protocols to prevent accidents, mainly due to the flammability of methanol. Furthermore, specific safety measures must be implemented during transportation, including secure loading and unloading procedures for tankers. Any accidents involving tankers or pipeline damage could pose environmental risks, making safety protocols essential for mitigating potential hazards associated with methanol use [32].

Though it is not considered a major obstacle, the infrastructure necessary for methanol production and distribution warrants attention. As a liquid, methanol is easier to store and transport compared to gaseous carriers like hydrogen. However, establishing a robust supply chain will require some modifications to existing infrastructure. For widespread adoption, it will be essential to upgrade specific components of the fuel infrastructure to accommodate large-scale methanol use, especially in regions where it has not yet gained traction [33].

The combustion of methanol results in CO_2 emissions, contributing to greenhouse gas emissions. To establish methanol as a genuinely sustainable energy vector, capturing the CO_2 generated during combustion is crucial. This captured CO_2 can be recycled in a closed-loop process to synthesize methanol again, thus creating a carbon-neutral cycle. However, the effectiveness of this approach hinges on developing and deploying efficient carbon capture and storage (CCS) technologies, ensuring that methanol remains a low-emission energy carrier [34]. Right now, there is a significant challenge towards scaling up CCS, which will have to accompany methanol production in a proportional manner [35].

Ammonia, another hydrogen-derived carrier, benefits from over a century of established technology and processes for its production. Ammonia is the second most-produced chemical worldwide, making it highly relevant in terms of industrial application. However, despite its widespread use, it is important to note that ammonia synthesis, mainly through the Haber-Bosch (HB) process, requires high pressures and temperatures, demanding significant energy, often derived from the combustion of fossil fuels [36]. This reliance raises concerns about the overall sustainability of the process. While the Haber-Bosch process has proven effective for large-scale industrial applications, there is an urgent need to enhance its efficiency by developing methods that operate under milder reaction conditions. Concurrently, innovative production techniques, such as photocatalytic and electrocatalytic processes, should be explored for ammonia synthesis to tackle these challenges effectively [37].

In addition to production efficiency, the purification of ammonia from the mixed gas (NH_3, N_2, and H_2) generated during the Haber-Bosch process is crucial for the effective use of ammonia as an energy carrier [37,38]. The purity of ammonia significantly influences its performance in subsequent applications. Currently, ammonia separation is achieved through physical condensation following industrial synthesis. However, this method often yields unsatisfactory efficiency due to the complexities of vapor-liquid equilibrium [37]. To improve ammonia purification, alternative methods such as liquid absorption and solid adsorption are being explored. These routes may offer more effective solutions for achieving the high purity levels necessary for ammonia's optimal utilization as an energy carrier since it can considerably save cost and energy consumption [37,38].

Besides the already mentioned carriers, there are other options that are yet under research, and may become feasible solutions in the future. Liquid organic hydrogen carriers (LOHC) are a class of molecules that covalently bind H_2, such as benzene/cyclohexane, methylcyclohexane/toluene, or decalin/naphthalene, to name a few. These compounds have advantages like being cheap and widely available, but they have high energy barriers for the dehydrogenation process, requiring high temperatures to release the stored H_2. Thus, the widespread use of LOHCs awaits further development, mainly in the field of catalysts [32].

1.1.3 Seaports and External Entities

Ports function as vital hubs where all maritime-related economic activities converge, exerting a significant impact on the environment and contributing to the development of local communities through job creation, wealth generation, leisure opportunities, and overall well-being. As gateways between sea and land, ports play a pivotal role in connecting maritime and terrestrial services. Their unique position enables them to actively contribute to the transition towards sustainability by fostering growth in their hinterlands and promoting the development of port cities.

Leveraging their strategic position and influence, ports can drive transformative changes in industries within their hinterlands. This includes advancing the energy transition for ships by promoting technical and operational energy efficiency measures and advocating for the adoption of clean marine fuels such us hydrogen, ammonia or biofuels. Ports can further support the energy transition in maritime transport by implementing initiatives like cold ironing and offering incentives such as green port fees. Moreover, ports can set a benchmark in sustainability by investing in hydrogen, energy efficiency, renewable energy sources, and electrification within their own operations, ultimately aiming to establish Net Zero Emission Port Terminals. However, to achieve these goals, it is pivotal to address several challenges. From a general perspective, major technical barriers to be overcome include:

- Applicability of H_2 engines or H_2 fuels to the equipment used for logistics and transport in and around ports: using Liquid H_2 (LH_2) for ships propulsion or even trucks, cranes, reach stackers requires important modifications of this equipment: the engine but also the tanks used for storing H_2 on board. Even though demonstrators exist for small vessels, they generally use double propulsion mode or H_2 fuel cells and batteries. It is to be noticed that very few studies have been carried out with port logistic equipment providers. Currently the feedback is that they do not consider H_2 as an alternative to gasoil. There is a general tendency at considering methanol –and e-methanol – or LVH which does not require to modify the motorization;
- The large spaces required to install H_2 production plants while ports generally lack space to develop their activities: the land required to host the electrolyzers and the storage tanks is another possible barrier for port generally concentrated on spaces constrained by cities or industries around. The problem is also linked to the SEVESO area that must be established around the installation to manage all safety requirements regarding other activities. The solutions are in the "miniaturisation" of the H_2 production module and in better specifications of risks and safety perimeters.

In particular, the barriers and challenges can be divided into categories, as proposed below:

i. **Ships and powering**

Developing and implementing the technologies necessary for the use of alternative fuels and energy storage by any type of vessel in the port area. This includes port service vessels such as tugs, pilots and other port operating vessels. It is also necessary to analyze the specific needs of fishing vessels depending on their activity. This poses the challenge of offering tailor-made solutions for the different types of vessels under consideration:

- Adaptation of new propulsion systems according to the type of vessel;
- Power supply for medium and long distances;
- Supply chain of new energies (H_2, Ammonia, etc.) for fishing vessels all over the world;
- Specific solutions for small vessels with very specific operations and needs, for example traditional fishing vessels;
- Advance the development of new propulsion technologies based on the use of hydrogen;
- Advance the development and implementation of dual engines to guarantee autonomy in long distance vessels;
- Advancing offshore bunkering and storage solutions such as mobile floating platforms to ensure access to fuel outside onshore supply zones;
- Advancing technological development for the implementation of floating platforms for energy production and storage using new hydrogen-related technologies.

ii. **Seaport electrification and management**

- Develop Infrastructure for alternative fuel generation;
- Developing and implementing the necessary technologies for alternative fuel generation, energy storage, consumption and efficient energy use;
- Space within the port to allocate infrastructure for hydrogen production and storage;

- Advancing in the energy self-sufficiency in ports through the implementation of renewable energy technologies, such as MRE, to ensure the necessary energy production to support green hydrogen;
- Scalability and Replicability: developing solutions that are scalable and replicable across different ports and maritime regions, allowing for widespread adoption and maximum impact;
- Global standardization for integration and Interoperability: Ensuring seamless integration and interoperability of different energy systems, technologies, and infrastructure to optimize energy use and minimize energy losses.

iii. Distribution

- Development of a global supply infrastructure: Currently, hydrogen production, transport and storage infrastructure at local, regional, national and international levels is very limited. The main challenge is to adapt existing infrastructure and build new infrastructure to support the generation, storage and distribution of alternative fuels.

In brief, for seaports, H_2 (like ammonia) are hardly considered yet as a mature market for port and maritime transport activities. The points mentioned above should be solved under the next 3/5 years to expect a real deployment of H_2 in the maritime sector. The development of hydrogen refueling stations within the port area is also crucial to ensure the continuous operation of hydrogen-powered machinery. Moreover, the current lack of available models of vehicles and machinery designed to run on hydrogen can hinder immediate adoption.

1.2 Economic Challenges and Barriers

1.2.1 Marine Renewable Energy

The significant amounts of energy and water required for hydrogen production through electrolysis can lead to substantial operational costs. However, in the long term, the shift to hydrogen can lead to cost savings through reduced dependency on fossil fuels and lower emissions-related expenses. To achieve these goals, however, one must equally consider i) significant capital expenditures for developing, manufacturing, transporting and installing MRE technologies, and ii) investment risks and Final Investment Decision (FID) strangleholds inherent to the technical uncertainties of existing technologies. In fact, many of the listed technical challenges and barriers will reflect upon the economic ones. According to the European Commission, "*the EU countries and private sector have invested more than €4 billion over the last ten years in research and pilot projects on ocean energy. Through the Strategic Energy Technology (SET) Plan, the EU has set cost-reduction targets on ocean technologies for the next decade. For tidal stream technologies, the costs should come down to €0.15 per kWh by 2025 and €0.10 per kWh by 2030, and for wave energy to €0.20 per kWh by 2025 and €0.15 per kWh by 2030*." Offshore wind estimates point towards €0.065/kWh [4]. As such, offshore wind is positioned as the most cost-effective option in upcoming years, but all three will see fierce competition from more established and mature alternatives, particularly onshore wind and solar, which exhibit significantly lower costs. Furthermore:

- ***Offshore wind***: according to [7], in one of the "*its largest offshore wind insurance markets, Germany and Central Eastern Europe*", it was seen that "*53% of offshore wind claims by value from 2014 to 2020 relate to cable damage, followed by turbine failure as the second major cause (20%). From the loss of entire cables during transport to the bending of cables during installation, cable losses have incurred multi-million-dollar losses in offshore wind as cable failure can potentially put a whole network of turbines out of commission*". Furthermore, the ambitious targets equally set for onshore wind will increase competition for common equipment, materials, components and personnel. This, alongside the aforementioned milestones for offshore wind and all the inherent requirements to achieve them, ought to exert significant pressure upon the supply-demand chains, already strained by external factors (*e.g.*, conflicts, inflation, material/labour scarcity and distribution, among others). Additionally, there are risks related to price fluctuations in global markets, not only for raw materials and components but equally with regards to the price of alternative energy sources, which may be beneficial or detrimental towards the goals of offshore wind. Europe, in particular, is very susceptible to external factors and imports, at the present time, being its dependency from non-European suppliers, a constant risk to consider. Investments of public and private nature may also be volatile, depending upon regional or global contexts and the perception of offshore wind to the markets, institutions, stakeholders and communities, as addressed in 2.3. It will be vital to further reduce the Levelized Cost of Energy (LCoE) through numerous supporting measures, investments and R&D efforts. Otherwise, investors and stakeholders may perceive offshore wind as an investment with increasing risk and uncertain pay-off, particularly as the sector escalates and moves further offshore;
- ***Wave energy***: again, wave energy ought to face similar challenges to those listed for offshore wind, to which add those related to its own low degree of maturity and absence of a design standard. Wave energy has seen significant investments over the past decades, but the LCoE remains too high for sizeable commercial projects to take shape. A path analogous to that of other energy sources ought to be taken, particularly in terms of learning curves and viable demonstration at sea (*e.g.*, CorPower's device currently at Aguçadoura, which withstood significant storms in late 2023). This equally reflects upon investor perception of risk and profitability, as premiums may be higher for capital investment. The demanding nature of the ocean environment and the direct exposure to wave action will equally present significant risks attributed to operational expenditures, driving upwards the LCoE. It will be equally pertinent to ensure reliable estimates of the available resource and conversion efficiency, at the risk of either oversizing WECs and/or having lower annual energy production than expected (increased LCoE through lower denominator). Given the limited amount of available data from sea trials, this introduces an additional degree of uncertainty that might discourage investors;
- ***Tidal energy***: With LCOE typically reaching the 150 €/MWh range, with ambitious commitment to reduce between 90 and 135 €/MWh in 2030 for the most favorable deployment conditions [19], tidal energy costs remain high compared to other sources of renewable energy. Several technologies and concepts are gradually gaining in maturity, with the horizontal-axis turbines being the most common concept being developed, which is expected to drive the costs down. This is supported by the first pre-commercial tidal currents farms hitting the water around

Europe (TIGER project[1], FLOWATT project[2]), opening the way to future commercial deployments. Tidal stream energy is facing several important challenges for cost reduction, including the harshness of the marine environment and the very high level of specificity of each tidal site (extreme currents, nature of the seabed, turbulence, limited weather windows, etc.). An important one is the limited number of suitable locations for tidal energy generation. The areas with sufficient resource to possibly make tidal energy economically viable are well known, especially around the Republic of Ireland and France for the Atlantic Area. This geographical limitation means that tidal energy cannot be as widely implemented as other renewable sources, restricting the potential for large-scale deployment and the setting-up of an industrial supply chain. Combining sufficient resource levels with high energy production costs such as in remote off-grid areas, would contribute to making tidal energy economically viable. Some projects, combining hydrogen production and storage from tidal streams have been set-up in Ushant Island in late 2022 with mixed results[3]. In that sense, tidal energy is more considered as a niche market. Developing technologies that can efficiently harness energy from less energetic tidal streams would lead to increasing a lot the surface available for tidal energy deployment and support the economic viability of that sector.

1.2.2 Energy Carriers

The economic impact of implementing hydrogen in ports is multifaceted. Initially, there are high capital expenditures required for the development of hydrogen infrastructure, including production plants, storage facilities, and distribution networks.

One of the main economic challenges of using green hydrogen as an energy carrier is the cost of electricity required for its production. International Energy Agency (IEA) compared the cost of hydrogen produced by different energy sources (green and not green H_2) and, for the cases employing low carbon energy sources, the price was above 3 USD per kg of hydrogen produced, while other sources presented lower values [33].

However, the same reference shows that hydrogen produced with energy from emitting sources but coupled with CCS also had prices below 3 USD. Thus, blue H_2 and other carriers can serve as an option for the transition to sustainability. IEA also states that the cost of renewable/clean energy is expected to drop, which eventually will cause a reduction in the prices of green hydrogen.

The Office of EERE presented short and long-term goals for the (production) price of a kg of H_2: 2 USD by 2026 and, ultimately 1 USD [27].

Also in the production sector, the price of electrolyzers plays a role in the economic impact of using green H_2. Alkaline electrolyzers are cheaper, since they use materials like cheap steel and nickel alloys. PEM electrolyzers require higher investments due to the materials they contain, like iridium. Solid Oxide electrolyzers are also expensive, but it is hypothesized that further research and optimization may bring the prices down. The two factors mentioned so far - price of energy and the cost of electrolyzer - seem to affect the industry's opinion. According to [34], industry would choose a cheaper

1 https://interregtiger.com/
2 https://www.flowatt.fr/
3 https://www.sabella.bzh/actualites/lile-douessant-experimente-lutilisation-dhydrogene-renouvelable-a-partir-de-lhydrolienne-d10/

but less efficient electrolyzer for locations where renewable energy is cheap, while they would invest in more efficient equipment in a location where electricity is scarce. Table 2 compiles the prices of electrolyzers according to OIES, in 2022.

Another factor that impacts costs is that the stacks of electrolyzers overtime require replacement. They may work for 3.5 to 11.5 years, depending on the type of electrolyzers, and factors like current density, temperature and pressure at which they operate, as well as water purity.

Table 2. Cost and durability of electrolyzers [13].

Type of electrolyzer	Investment cost/(USD/kW)	Stack lifetimes/hours
Alkaline	540-900	60 000 – 100 000
PEM	667-1450	50 000 – 90 000
Solid Oxide	2300-6667	20 000 – 90 000
AEM	>931	30 000

Apart from production costs, using H_2 as an energy carrier may incur additional costs related to transportation, particularly due to its low energy density. A study from South Korea [36], driven by the interest in importing hydrogen from Australia - where favourable sunny conditions allow for low cost green H_2 production - analyses the costs of liquefying hydrogen for transport by ship. According to the study, it requires 23.7 kWh of energy to liquefy 1 kg of hydrogen. Beyond the energy needed for compression and cooling, there is another cost factor: hydrogen may exist in two forms - ortho and para. Para-hydrogen is more stable, and the transition between the two forms releases heat, which can cause vaporization during transport. To mitigate this, ortho-to-para conversion is induced beforehand, which introduces additional costs due to the energy requirements and the use of catalysts. The study also identifies compressors as the main component of liquefaction costs. Notably, the cost of liquifying H_2 is higher than for other gases, due to the temperature and pressure requirements. Furthermore, the extreme operating conditions contribute to the high maintenance costs of liquefaction facilities [36].

Ammonia and methanol are liquid at room pressure and temperature, and may present an attractive alternative to H_2. The volumetric energy density is a useful parameter to compare fuels, particularly for transport. Values of volumetric energy densities are presented in Table 3.

Table 3. Volumetric energy density for hydrogen, ammonia and methanol [37].

Molecule	Volumetric energy density/(MJ/L)
Hydrogen (liquid)	10
Ammonia	12
Methanol	16

Regarding the use of ammonia, the current challenge is to make the transition to a decarbonized production, particularly in what concerns the source of energy used. However, the transition is hampered by costs: a ton of green ammonia costs 720 USD – 1400 USD, six times more than the non-green ammonia [38].

With respect to methanol, costs arise from the low efficiency of the reaction that forms methanol. The low efficiency of conversion of reactants reflects in the need of recycling the unreacted species, which

has costs of separation and pumping. Moreover, the separation of methanol from the side-produced water requires distillers, which are expensive and energy-consuming.
LOHCs are also a promising option for transport since preexistent infrastructure could be used to store them, but problems at the level of the energy required to dehydrogenate them still prevent their widespread application.

1.2.3 Seaports and External Entities

Ports that adopt hydrogen technology can gain a competitive advantage by attracting environmentally conscious customers and aligning with global sustainability trends, potentially increasing their market share. However, economic viability heavily depends on overcoming the barriers related to the high initial costs and ensuring a consistent supply of green hydrogen. As such, the following barriers and challenges were identified:

i. Ships and powering

- High investment cost of building hydrogen-powered ships or re-converting and/or retrofitting existing ships;
- Potentially insufficient technological maturity to ensure energy sufficiency in the displacement and operations of the vessel, in order to finance its implementation;
- Price of green hydrogen for deployment as a fuel, even when compared to other energy carriers like methanol;
- Lack of financial incentives to facilitate the adoption of new propulsion technologies for vessels, despite the significant investments in hydrogen implementation in other sub-areas;
- Dilemma imposed on port authorities with regards to green taxation of shipping activities and re-fueling (e.g., greenhouse gas – GHG – tax for operating within the seaport area), as unequal rates will promote route migration towards ports with lower tax impositions.

ii. Seaport electrification and management

- Financial incentives and support programs to deploy cold-ironing or electricity supply infrastructures for ships moored in ports;
- Financial support to advance in energy self-sufficiency in ports implementing renewable energies, including MRE.

iii. Distribution

- Funding and Investment: Securing funding and investment to support the research, development, and implementation of sustainable energy solutions in ports and maritime sectors, as well as establishing adequate, yet costly transit corridors (e.g., mainland pipelines or vessel carriers for port-to-port transport);
- Define the most cost-effective means of distribution for each region and hinterland without compromising standardization and compatibility of the transport networks.

1.3 Social Challenges and Barriers

1.3.1 Marine Renewable Energy

MRE has an inherently positive social perspective in terms of “green” energy transition, climate change mitigation and “Blue Economy”. Even so, there are social perceptions that may endeavor ongoing efforts toward MRE deployment, namely:

- ***Offshore wind***: offshore wind turbines, like their mainland counterparts, are susceptible to the “Not In My BackYard” (or NIMBY) mentality. Not only is there a visual impact, in this case associated with coastal communities (albeit reduced further away from the shoreline), but also a competition with other marine space uses. Such conflicts include more established activities (*e.g.*, touristic routes, shipping lanes, fishing areas, offshore oil and gas platforms, etc.), but can extend to developing “Blue Economy” markets (*e.g.*, offshore aquaculture and other MRE technologies) or overlap with protected areas (*e.g.*, Europe’s Natura 2000 network). There are opportunities for co-location and to benefit from existing expertise from other offshore industries, but public perception may vary depending on the combinations, as found in [39]. The characteristics and awareness (or lack thereof) of local communities may sway the support towards offshore wind and, by consequence, H_2 production at seaports. The aforementioned conflicts can bring about direct confrontation (*e.g.,* resistance from local communities to the entry of offshore wind, which may lead to prolonged and expensive judicial procedures), job losses (*e.g.*, expulsion/nullification of existing jobs related to the marine space allocated to offshore wind) if inadequate retraining and compensations are provided, environmental contradictions (*e.g.*, occupation and artificialization of marine space, interference with local fauna and flora, and endangering of migrating routes of marine species), visual impacts and potential changes to the local climate, among other concerns. The perception of investments and expected return is equally important, as the implementation of MRE such as offshore wind will require large expenditures. As such, local communities will expect benefits from such an investment, such as lower energy costs and reliable supply systems. Project failures, shutdowns, budget offsets and delays can hamper the support provided to offshore wind deployment. This extends to the political level, which in Europe is susceptible to electoral cycles and changing priorities. As such, transparency, consistency, economic viability and reliability will be crucial towards a supported deployment of offshore wind;
- ***Wave energy***: in the medium-to-long term, similar challenges to those listed for offshore wind are equally expected for wave energy, from marine space conflicts to return on investment. Regardless, WECs have generally lower visual impact than offshore wind turbines (*i.e.*, smaller profile above the waterline), but their occupation of marine space (*e.g.*, water column and seabed) may be more significant depending on device typology. The difference in capacities also implies a greater number of WECs than wind turbines, in order to achieve similar energy outputs. At an environmental level, this can bring about additional impacts, from magnetic fields to disturbance of the seabed. Unlike offshore wind, wave energy is not as mature or as established, which corresponds to a lower degree of awareness by local communities. This will imply additional educational efforts by researchers, policy makers and stakeholders. The currently higher costs of wave energy may further contribute to the aforementioned perception of return

on investment. Given the limited data available from sea trials and the absence of fully validated and commercial technologies, reliability is an even greater barrier to overcome than for offshore wind;

- ***Tidal energy***: So far, the development of tidal energy is too scarce and benefits from a generally low visual impact to get significant awareness from the general population, unlike wind energy. Still, and considering the very local and site-specific aspects of that technology, the early consultation of the local communities regarding space conflicts, visual and environmental impacts, etc. is a prerequisite to successfully complete this kind of project. Good practices and recommendations include involving professional and local communities in the governance of the project to address all the local sensitivities and lift or anticipate any possible objection. Regarding the tidal energy industry, there has been a limited number of success stories (Hydroquest, Eel Energy), and many more failures (Open Hydro, Sabella, etc.). Tidal energy consequently remains a risky investment with limited impact on the employment area.

1.3.2 Energy Carriers

From a social perspective, the adoption of hydrogen in ports can lead to significant environmental benefits, contributing to improved air quality and public health in surrounding communities. The reduction of greenhouse gas emissions and pollutants from port activities helps mitigate climate change and supports the overall sustainability goals of the region. However, there are social challenges to consider, such as the general lack of knowledge about hydrogen technology and its associated risks. This includes understanding the maintenance required and the safety protocols necessary to handle hydrogen. Thus, successful implementation of hydrogen infrastructure at seaports requires overcoming numerous social challenges in order to galvanize public acceptance, economic viability, and seamless integration with existing systems. This sub-section outlines the primary social challenges and barriers associated with hydrogen implementation at seaports, focusing on public perception, stakeholder engagement, workforce development, regulatory frameworks, and environmental justice:

i. **Public perception as a key factor influencing the successful adoption of hydrogen technologies at seaports**
    - Safety Concerns: Hydrogen is flammable, and its storage and transportation raise safety concerns among local communities and port workers, particularly in non-specialized individuals. Alike perceptions regarding toxicity, emissions and contamination by ammonia and/or methanol can further exacerbate such concerns. Misunderstandings about the risks of energy carriers can, thus, result in public resistance and, consequently, reduced support from stakeholders, investors and even politicians. These fears are often driven by misconceptions about energy carriers' explosive potential and/or environmental impact;
    - Lack of Knowledge and Awareness: There is a general lack of public understanding about the benefits of hydrogen, methanol and ammonia as clean energy carriers, mainly when the energy source derives from renewables such as MRE. The same applies to safety protocols and the technologies used for production and storage. Communities may not fully grasp the role hydrogen and other energy carriers can play in reducing emissions, leading to skepticism on its potential and implementation benefit. This absence of awareness can be

as basic as understanding the main differences between the distinct enery carrier typologies, or even the alternative electrolysis technologies (*e.g.*, asking a non-specialized public group to distinguish between a PEM and an Alkaline electrolyzer).

ii. **The involvement and collaboration of diverse stakeholders, including port authorities, shipping companies, energy providers, local communities, and government agencies, is crucial to the success of hydrogen projects**

- Lack of Collaboration and Coordination: Disparate objectives among stakeholders can result in fragmented efforts (*e.g.*, splitting investments between distinct energy carrier storage and distribution networks, making them potentially incompatible and losing out on economies of scale and shared connections). For instance, shipping companies may not align their hydrogen adoption strategies with port authorities' infrastructure development plans: ports could focus on compressed or liquefied hydrogen networks while the shipping industry focuses on constructing methanol-fueled vessels, as an example;
- Competing Interests: Differing priorities, such as economic growth versus environmental sustainability, can create conflicts. This misalignment can slow progress and lead to opposition from stakeholders who prioritize short-term financial gains over long-term environmental (and even indirect economic) benefits. This uncertainty, alongside shifting targets and milestones set by investors and even public entities (e.g., moving deadlines further into the future or reducing the amount of energy carrier production by a certain timeline), further discourages stakeholders and raises concerns regarding economic viability and risk, which are negative perceptions. This equally affects public perception, which may become skeptical of the actual implementation of proposed measures and even suspect certain inappropriate actions, from corruption to “green washing”.

iii. **The transition to hydrogen has significant economic implications that may create barriers to its adoption, particularly for workers and communities dependent on traditional energy sectors**

- Job Displacement: Workers in fossil fuel industries may face job losses as hydrogen displaces traditional energy sources. This can lead to resistance from affected communities, especially if there is no clear plan for retraining or employment in the new hydrogen economy. Slow repurposing efforts may also discredit the transition process (*e.g.*, an oil refinery shutdown in Matosinhos, Portugal, by early 2021 that still hasn´t been retrofitted for other purposes, namely related to hydrogen production and/or R&D within the fields of “Blue Economy”;
- High Investment Costs: Hydrogen infrastructure development, including production, storage, and distribution facilities, requires substantial investment. While methanol and ammonia may provide more attractive solutions, from an economic perspective, they are not without financial risks and significant capital investments. Communities may express concerns about the allocation of public funds and whether the economic benefits, such as new jobs and energy tariffs, will be equitably distributed. Implementation delays and/or budget deviations can further erode social trust in energy carrier endeavors at seaports.

iv. The absence of a clear regulatory environment can create uncertainty for hydrogen adoption at seaports

- Lack of Coherent Regulations: The current regulatory landscape for hydrogen and alternative energy carriers is often fragmented and underdeveloped (see Section 2.4), leading to delays in project approvals. Uncertainty around safety, environmental compliance, and investment incentives discourages stakeholders from committing to hydrogen projects, given the excess risk inherent to such endeavors. Alternating political cycles and priorities can also jeopardize continuous investments and efforts;
- Inconsistent Government Policies: Inconsistent or inadequate policy support for energy carrier technologies can create confusion among investors and communities, further delaying the implementation of hydrogen infrastructure. Changing milestones, financing formats (e.g., auctions and grants), or even providing inadequate and inconsistent deadlines are examples of such occurrences. Furthermore, in Europe, there is common legislation that is adapted to each member state, but there are also national goals and legislation to consider (see Section 2.4). This requires extensive knowledge and research that needs to be conducted for each region, mainly in international consortia and projects. The absence of a clear, unique set of rules and procedures makes it even harder for stakeholders and investors to be willing to partake in hydrogen implementation efforts at seaports.

v. Building hydrogen infrastructure at seaports presents logistical and operational challenges, particularly regarding integration with existing port operations

- Disruptions During Construction: Developing energy carrier facilities and equipment, such as storage tanks and refueling stations, may cause temporary disruptions, including noise, traffic, and land use changes (e.g., competition for space to allocate port infrastructure). Communities affected by these disruptions may resist hydrogen projects if they perceive a lack of immediate benefits;
- Integration with Existing Systems: Ports are complex logistical hubs, and integrating hydrogen infrastructure into existing systems without disrupting current operations can be challenging. This can lead to resistance from stakeholders accustomed to traditional energy sources. The retrofitting process will also be quite challenging from a technical perspective, implying high costs that may not be well perceived by stakeholders or even the general public.

vi. The transition to hydrogen must consider social equity and environmental justice, particularly in communities already burdened by pollution and seaport industrial activity

- Equitable Distribution of Benefits: Hydrogen projects should benefit all community members, including marginalized groups. There is a risk that some local communities will bear the environmental, economic or social costs of hydrogen development while others mostly benefit from the efforts;
- Environmental Impact: Communities may express concerns about the environmental impact of energy carrier infrastructure and fuel production, particularly if the energy carriers are derived from non-renewable sources (e.g., "grey") or if local ecosystems are

threatened by construction activities and/or hazards inherent to the production, storage, distribution and/or usage of hydrogen and other energy carriers at seaports.

1.3.3 Seaports and External Entities

The transition to hydrogen can foster local economic development by creating new job opportunities and training programs focused on clean energy technologies. Engaging with the local community and stakeholders throughout the implementation process is essential to address any concerns and ensure public support. Promoting awareness and education about the benefits and safety of H_2 can further enhance social acceptance and participation in the transition towards a cleaner port environment. Regardless, this can only be achieved by overcoming the following challenges and barriers:

- *Public Awareness and Acceptance*: inadequate engagement with local communities, misinformation and incorrect awareness raising efforts can drive away support for deployment of hydrogen technologies at seaports, following on the NIMBY mindset issues already identified in some instances, as is the case with offshore wind;
- *Environmental Impact Assessment*: following on the previous point, public perception will also be affected by unwanted consequences of H_2 implementation, including eventual negative environmental impacts. These can be either direct (*e.g.*, energy carrier leakage and contamination of habitats) or indirect (*e.g.*, non-renewable sources to produce H_2 or the impactful extraction of critical raw materials to produce electrolyzers). Port authorities are required to manage the harbor area and can be held responsible for negative impacts in its vicinity, as well as for the decision-making process and strategy towards the H_2 integration process. Social perception of their actions and decision can be negatively affected by environmental impacts associated with the energy adaptation efforts, as they will seem contradictory with the baseline premise of green transition and may directly affect local communities;
- *Knowledge and Skills*: the ongoing green energy transition implies the shutdown of several fossil fuel-based companies and entities, which can lead to job extinction in some sectors. In the absence of re-skilling and training programs to adapt the affected workers to new functions related to H_2 integration within seaports, there is the risk of loss of human potential and widespread discontent against this implementation process, from a cost-benefit and social perspective. Insufficient knowledge sharing and worker training also hamper the technological development, implementation and O&M of hydrogen-based systems at seaports;
- *Stakeholder Engagement*: without a suitable connection and partnership promotion between industrial, commercial, port authority and academic partners, the viability of H_2 projects at seaports can be jeopardized significantly, from deployment delays to operational failures or even project shutdown. This can negatively impact public and stakeholder perception of hydrogen projects at seaports, making them less willing to support such endeavors in the future;
- *Safety*: there are hazards and risks inherent to handling and processing energy carriers like methanol, ammonia and hydrogen. Each of these solutions presents unique challenges to be overcome at many levels, as seen beforehand, but the social perception is equally important. With the ongoing green energy transition, any noteworthy perception of risk, damage or even causalities can shift public opinion and investor interest away from H_2 integration into seaports.

1.4 Legal Challenges and Barriers

The 2023 International Maritime Organization's strategy for GHG emissions foresees a reduction in carbon intensity of international shipping, particularly for CO_2, by at least 40% by 2030. This is set as an average across international shipping, and extends to the uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources. It is expected that they will represent at least 5% to 10% of the energy used by international shipping, by 2030. Furthermore, the EU has introduced regulations to promote renewable hydrogen as part of its decarbonization efforts. These regulations apply to both domestic and international producers exporting to the EU. A critical component is the additionality requirement, which requires hydrogen production to be paired with new renewable energy generation capacity. This ensures that the increase in hydrogen production does not rely on existing renewable electricity but drives the development of new capacity [40]. However, this requirement may create a bottleneck in the widespread adoption of hydrogen, as it demands significant investment in renewable energy infrastructure to meet hydrogen production needs. The large-scale production of hydrogen will necessitate substantial new renewable capacity, which could delay the scaling up of hydrogen, especially if renewable energy projects do not grow at the same pace as hydrogen demand.

REPowerEU is a European Commission plan launched in response to the energy crisis caused by Russia's invasion of Ukraine. The plan aims to reduce the EU's dependence on Russian fossil fuels and accelerate the transition to renewable energy sources. A key objective of REPowerEU is to promote the production and use of renewable hydrogen to decarbonize industries and transportation [41]. As part of this plan, the EU aims to produce 10 million tons of renewable hydrogen annually by 2030. To achieve this, the region will need 90-100 GW of electrolyzer capacity to generate sufficient hydrogen within the EU [42]. Electrolyzer manufacturing is another major bottleneck in the hydrogen economy. According to the International Energy Agency (IEA), the current global electrolyzer manufacturing capacity is around 8 GW per year, which is far below what is needed to meet Europe's targets [42]. To accelerate the hydrogen economy, the European Commission has set a target to increase the EU's electrolyzer manufacturing capacity to 17.5 GW per year by 2025 [43]. This scale-up is crucial to meet the ambitious goals of the REPowerEU plan. Compounding these issues, rising raw material costs and competition from other industries have made it difficult to scale up electrolyzer manufacturing [44].

End-use infrastructure bottlenecks present a significant challenge in the development of the hydrogen ecosystem. One prominent example is the slow deployment of hydrogen refueling stations (HRS). The development of HRS remains a critical obstacle to hydrogen adoption, particularly for heavy-duty vehicles (HDVs). The EU's Alternative Fuels Infrastructure Regulation (AFIR) mandates the installation of HRS every 200 km along the Trans-European Transport Network (TEN-T) by 2030 to support both light and heavy-duty vehicles [45]. Meeting this ambitious target will require significant infrastructure expansion, especially for HDVs, which have more demanding fueling requirements. While some countries, such as Germany, are advancing rapidly (Germany has 105 hydrogen stations as of 2023, nearly 40% of Europe's total), other EU member countries are lagging behind. This disparity slows the adoption of fuel cell electric vehicles (FCEVs), particularly in the commercial transport sector, where hydrogen-powered HDVs are essential [46].

1.4.1 Portugal

Portugal's strategy for MREs has been consolidated over the last few years, ranging from individual projects (*e.g.*, WindFloat Atlantic) to more encompassing strategies within the national and European contexts. An important milestone was achieved through the "OffshorePlan - Planning the Use of Offshore Renewable Energies in Portugal (POSEUR-01-1001-FC-000007)", directed by the National Laboratory of Energy and Geology (LNEG) [47]. This work has been extended through a technical report by the Directorate-General for Natural Resources, Safety and Maritime Services (DGRM) in 2023, in which topics such as available MRE resources, typology of MRE technologies, marine space restrictions, bathymetry and seabed composition were overlapped to establish viable MRE deployment zones. The Offshore Renewable Energy Allocation Plan (PAER) [48] defines several zones along the Portuguese coastline for which deployment of MRE technologies is viable, Figure 1. This accounts for the outtakes of local stakeholders. For instance, the proposal was submitted in an online open-access platform – Participa.pt – for public consultation and feedback, resulting in an update to the document following concerns expressed by several offshore industries, such as fishing.

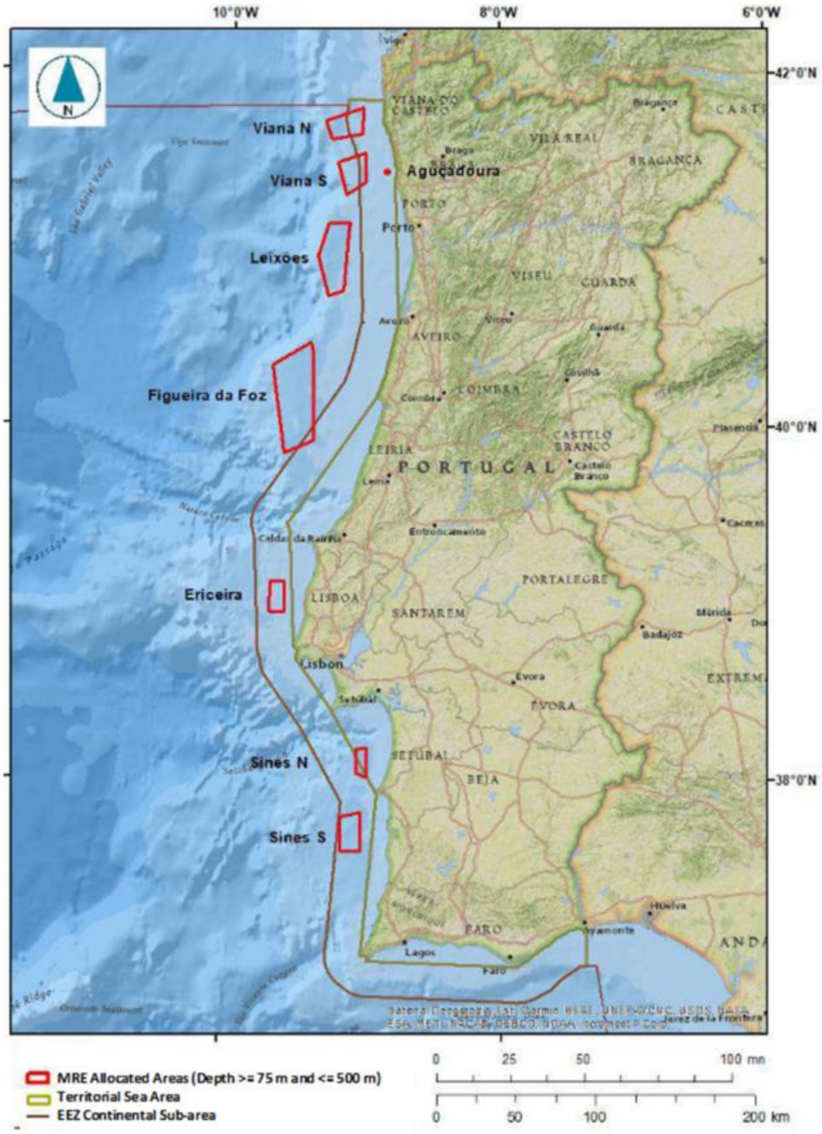

Figure 1. Areas for deployment of MRE in Portugal, adapted from from [48].

It is worth noting that these efforts required significant time and effort to ensure a solution accepted by all involved stakeholders and institutions, as well as compromises in terms of available areas for deploying MREs (*e.g.*, the latest version of the proposal required the exclusion of some areas from the original one). While this promotes social acceptance and public perception, it significantly restricts the available areas for MRE exploitation. Furthermore, while there are many available tools for public consultation (*e.g.,* the online geoportal of DGRM [49], which includes the PSOEM - Maritime Spatial Planning Situation Plan), there have been delays and alterations. For instance, it was initially expected to deploy, by 2030, about 10 GW's worth of MRE in the PAER's established zones [50], but this goal has been reduced to about 2 GWs in mid-2024. While the approach remains the same – auction-based with international competition for slots of the available PAER zones –, the milestone has been greatly reduced in the updated National Plan of Energy and Climate (PNEC2030) [51].

Another important matter is the absence of a recent licensing guide for MRE. While there is such a framework for onshore energy, provided by the Portuguese Renewable Energy Association (APREN), the latest document for offshore energy comes from the private company WavEC [52]. While useful for understanding the main legal components to be addressed, it is relatively outdated (originally form 2016) and does not reflect a binding legal framework, but rather a compilation of distinct components that need to be addressed cumulatively. The most recent supporting guideline is the aforementioned PNEC2030, which discriminates the contributions and milestones for offshore wind and wave energy, even for the national hydrogen objectives. Even so, a concerning matter is, among others, the outdated and simplified references for energy costs, as seen in Figure 2.

Custo das principais tecnologias de geração de eletricidade considerados no modelo TIMES_PT (preços €2016)

Tecnologia	Tamanho médio	Tempo de vida Técnico	Custos de Investimento (CAPEX)				Custos Fixos de operação e manutenção				Custos Variáveis de operação e manutenção (exc. Custos de energia)				Ref.
			2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	
Unidade:	MW	anos	EUR/kW	EUR/kW	EUR/kW	EUR/kW	EUR/kW	EUR/kW	EUR/kW	EUR/kW	EUR/GJ	EUR/GJ	EUR/GJ	EUR/GJ	
Gás Natural															
Gás Ciclo Combinado convencional	550	35	758,57	758,57	758,57	758,57	18,96	18,96	18,96	18,96	1,00	1,00	1,00	1,00	JRC (2013)
Gás Ciclo Combinado Avançada	550	35	618,72	618,72	618,72	618,72	12,43	12,43	12,43	12,43	1,00	1,00	1,00	1,00	EDP (2018)
Gás Ciclo Combinado com captura de CO2 pos combustão	550	35		1 226,00	1 193,00	1 160,00		44,00	43,00	42,00					JRC (2013)
Gas Ciclo Aberto (Peaker) Avançada (OGCC)	550	35	515,00	505,00	503,00	501,00	13,00	13,00	13,00	13,00	1,00	1,00	1,00	1,00	JRC (2013)
Hídrica															
Hidroelétrica de fio de água		70	1 450,00	1 339,00	1 226,00	1 209,00	15,00	13,00	12,00	12,00					(1)
Hidroelétrica Barragem (elevado capacity factor)		80	1 052,00	1 031,00	995,00	923,00	11,00	10,00	10,00	9,00	1,00	1,00	1,00	1,00	(1)
Hidroelétrica Barragem (baixo capacity factor)		80	1 052,00	1 031,00	995,00	923,00	11,00	10,00	10,00	9,00	1,00	1,00	1,00	1,00	(1)
Hidroelétrica Barragem com bombagem		80	809,00	792,00	765,00	709,00	8,00	8,00	8,00	7,00	1,00	1,00	1,00	1,00	(1)
Geotérmica															
Sistema Geotérmico Enhanced (Hot dry rock)		30	8 490,00	6 367,00	6 367,00	6 367,00	297,00	223,00	223,00	223,00					(2)
Geotérmica Hidrotermia com flash		30	2 335,00	2 122,00	2 122,00	2 122,00	82,00	74,00	74,00	74,00					JRC (2013)
Eólica															
Eólica offshore Flutuante		25	3 911,00	3 030,00	2 676,00	2 364,00	125,00	97,00	86,00	76,00					IRENA
Eólica Onshore		30	1 037,00	1 016,00	995,00	985,00	41,00	41,00	41,00	41,00					EDP (2018)
Micro Eólica		20	5 208,00	4 381,00	3 910,00	3 600,00	104,00	88,00	78,00	72,00					(3)
Ondas e Marés															
Ondas - tecnologia genérica	5	30	5 424,00	3 431,00	2 918,00	2 481,00	163,00	103,00	88,00	74,00					(4)
Marés - tidal stream	10	30	4 364,00	2 761,00	2 347,00	1 996,00	253,00	160,00	136,00	116,00					(4)
Solar Fotovoltaico															
Painel Solar Telhado (Silício Cristalino) - Residencial		30	1 409,00	1 345,00	1 299,00	1 245,00	31,00	31,00	31,00	31,00					(5)
Painel Solar Telhado (Silício Cristalino) - Comercial		30	1 057,00	1 009,00	974,00	933,00	28,00	28,00	28,00	28,00					(5)
Solar fotovoltaico centralizado (Silício Cristalino)	100	30	778,00	742,00	717,00	687,00	23,00	23,00	23,00	23,00					(5)
Solar fotovoltaico Alta Concentração		30	1 674,00	1 597,00	1 542,00	1 478,00	25,00	24,00	23,00	22,00					JRC (2013)
Solar Concentrado															
Central PTC de referência - 7,5 h armazenamento (molten salt)	160	25	4 012,00	2 346,00	1 790,00	1 460,00	100,00	59,00	45,00	37,00					(6)
Central PTC de referência - 9 horas armazenamento (molten salt)	150	25	4 021,00	2 265,00	1 728,00	1 410,00	101,00	57,00	43,00	35,00					

(1) TIMES_PT Database; REN data own Calculations for Afs; JRC (2013); EDP (2010). (2) JRC (2013). Capacity factor comunication from APREN (3)WWEA (2016); Distributed Wind market Report US (2016) (4)COGEA (2018). EC_Market Study on Ocean Energy (Wave and Tidal Stream). Available on: https://op.europa.eu/en/publication-detail/-/publication/e38ea9ce-74ff-11e8-9483-01aa75ed71a1 (5) EDP (2018). FIXOM Ajustados pela APREN (2018) (6) ES capacity data for short term + JRC(2013) in 2050

Referências - Tecnologias

JRC (2013). The JRC-EU-TIMES model. Disponível em: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC85804/jrc_times_%20eu_overview_online.pdf

"EDP (2018). Comunicação pessoal EDP durante a realização do estudo THE ROLE OF ELECTRICITY IN THE DECARBONIZATION OF THE PORTUGUESE ECONOMY"

APREN (2018). Comunicação Pessoal da APREN

E3-Modeling 2022 - REF2020_Technology Assumptions_Energy

Figure 2. Annex I of PNEC [51].

There is also a stability risk that can drive away investors, since the execution and objectives of plans such as PNEC2030 can change significantly according to the national political situation (as was the case in 2024). Uncertainty regarding legal frameworks, deployment goals, auction details and bureaucratic procedures becomes a serious matter to consider, to which it adds the environmental aspects. For example, in Portugal, projects of this magnitude are necessarily subjected to an Environmental Impact Assessment (EIA), which can be lengthy, conditioned or even rejected, and implies several stages (declarations for the project and execution stages, issued by APA – Portuguese Environmental Agency). The PNEC2030 strategy for expanding renewable energy in Portugal outlines several initiatives, but it also highlights potential legal and legislative bottlenecks, barriers, and challenges that could hinder its implementation. As an extension to the previous considerations, one should also account for:

i. **Complex and Lengthy Licensing Processes:**
    - The process of obtaining licenses for new renewable energy projects, particularly offshore projects, can be complex and time-consuming due to regulatory requirements and the involvement of multiple stakeholders and authorities, as well as the absence of a recent, general outline of the legal procedures to be undertaken, from auction rulings to EIA detailing for MRE;

ii. **Grid Capacity and Integration Issues:**
    - The current capacity of the electricity grid to accommodate new renewable energy projects is limited. There is a need for significant investment in grid reinforcement and expansion to integrate additional capacity from renewables;
    - Coordination between the issuance of production licenses and the development of grid capacity is crucial to avoid bottlenecks;

iii. **Regulatory Uncertainty:**
    - Frequent changes in regulations and policies can create uncertainty for investors and project developers, as was the case with a government change in 2024 and the update of the PNEC. Stability and predictability in the regulatory environment are essential to attract investment and ensure the successful implementation of renewable energy projects;

iv. **Environmental and Spatial Planning Constraints:**
    - Offshore and onshore renewable projects must comply with stringent environmental regulations and spatial planning requirements (EIA and respective declarations), which can delay project approvals and increase costs.
    - Balancing renewable energy development with other uses of maritime and terrestrial areas (*e.g.*, fishing, tourism, conservation) can be challenging and restrictive, as seen in the updated version of the PAER. At an international level, there is also the risk of competition for space and grid access, particularly along shared borders and connections;

v. **Interconnection with Neighboring Countries:**

- The need for enhanced interconnections with Spain and France to balance electricity supply and demand, as well as to export surplus renewable energy and/or energy carriers such as hydrogen, faces regulatory and technical challenges;
- Coordinating policies and regulations across borders is necessary to facilitate the development of these interconnections. Failure to do so will severely restrict the intra and interconnectivity of the AA region, hampering supply and distribution chains, as well as prompt legal issues between the AA partners, which is counterproductive towards the cooperative necessity of such undertakings (*e.g.*, common distribution networks, territorial accessibility and compatible equipment and systems);

vi. **Market Design and Flexibility:**

- The current electricity market design may not fully support the integration of a high share of variable renewable energy sources like solar and wind, given the limited grid capacity. This may bring about legal issues with regards to grid access priority and expansion;
- There is a need for market mechanisms that provide flexibility and incentivize the development of energy storage and demand response solutions, as is the case with hydrogen and complementary energy carriers (see 2.4.2. for more details). As such, there should be a clear legal framework not only for standalone MRE, but also its compatibility and conversion into energy carriers for storage, supply and distribution purposes;

vii. **Financing and Investment Barriers:**

- Access to financing for large-scale MRE projects can be challenging, particularly for newer and less mature technologies like offshore wind and, particularly, wave energy;
- Public funding and incentives, along with private investment, are crucial to overcoming financial barriers, and legal support is required to de-risk such and bolster such investments;

viii. **Technological and Infrastructure Development:**

- Developing and deploying advanced technologies, such as floating offshore wind platforms and wave energy converters, requires supportive regulatory frameworks and targeted research and development funding (*e.g*, universities and MRE industry and companies);
- Infrastructure improvements, including port facilities and transmission lines, are necessary to support the deployment of offshore renewable energy projects;

ix. **Skilled Workforce and Training:**

- The expansion of the renewable energy sector demands a skilled workforce for installation, operation, and maintenance of new technologies;
- There is a need for training programs and educational initiatives to develop the necessary skills and expertise. Not only does this imply dedicated training validated by legal frameworks (*e.g.*, credited university courses), but also the establishment of legal procedures to be learned by specialized workers, from lawyers to insurance companies. Otherwise, without clear legal guidelines, there is a risk of lengthy and costly judicial processes;

x. Public Acceptance and Stakeholder Engagement:

- Gaining public acceptance and effectively engaging stakeholders, including local communities and interest groups, is essential for the successful implementation of MRE projects. This extends to political perception, as any project or legal framework approved by the ruling government is subjected to several risks, from lack of transparency/corruption to policy changes with alternating governments;
- Transparent communication and participatory planning processes can help address concerns and build support for renewable energy initiatives. The definition of the PAER, for instance, implied public engagement through the "Participa.pt" platform.

Addressing these legal and legislative bottlenecks, barriers, and challenges is critical to achieving Portugal's ambitious MRE targets and ensuring a smooth transition to a sustainable energy future.
Besides the aforementioned PNEC2030 strategy, additional regulations, laws, and decrees regarding H_2 implementation in Portugal are listed below:

i. National Strategy for Hydrogen (EN-H2): This strategy, established by the Council of Ministers Resolution no. 63/2020, aims to promote hydrogen as a sustainable pillar in Portugal's energy transition. It includes measures to boost hydrogen production, storage, transport, and consumption, as well as ambitious targets for 2030, such as achieving 5 % green hydrogen in final energy consumption in transport and industry, injecting 15 % of green hydrogen into natural gas networks, establishing 50 to 100 hydrogen refueling stations, and installing between 2 and 2.5 GW of production capacity through electrolyzers [53];

ii. Decree-Law no. 30-A/2022: Published on April 18, 2022, this law supports the simplification of licensing and administrative procedures for renewable energy projects, including hydrogen. A notable provision requires gas suppliers with an annual volume exceeding 2 000 GWh to incorporate a minimum of 1% biomethane or hydrogen produced via electrolysis from water into their natural gas supply. It aligns with the country's strategy to expedite green hydrogen projects and reduce bureaucratic barriers, with specific provisions that were later expanded by Decree-Law no. 72/2022 [53];

iii. Decree-Law no. 72/2022: This decree, published on October 19, 2022, introduced amendments to Decree-Law no. 30-A/2022, establishing exceptional measures to simplify the implementation of renewable energy production and storage projects. Key changes include exempting projects under 1 MW from prior control requirements. For projects over 1 MW, municipalities may only reject installations if renewable energy facilities already occupy 2% or more of the municipal territory, and the project does not have a favorable or conditionally favorable environmental impact declaration. Rejections based on potential landscape heritage impacts are not allowed [54];

iv. Decree-Law no. 84/2022: This decree-law established a legal framework for renewable gas production and commercialization, which includes green hydrogen and biomethane. It outlines the procedures for licensing, registration, and guarantees of origin for renewable gases, facilitating their entry into the national gas network [55].

v. Portaria no. 15/2023: Published on January 4, this ordinance establishes a centralized purchasing system for biomethane, and hydrogen produced via water electrolysis using renewable electricity, aimed at injection into the national gas grid. The specific quantities set are 150 GWh/year for biomethane and 120 GWh/year for hydrogen (both based on higher heating value). The ordinance also specifies that contracts will last 10 years from the date of first supply [56].

vi. Dispatch no. 30/2023: Issued by the Directorate-General for Energy and Geology (DGEG), this dispatch provides detailed guidance on the licensing and regulatory framework for renewable hydrogen production projects and facilities. It specifies the technical and operational standards for safe hydrogen production and sets requirements for environmental compliance and site inspections. The guidelines emphasize the importance of using renewable sources, such as electrolysis powered by renewable electricity, to produce hydrogen. Additionally, inspection entities are designated for facility oversight, ensuring ongoing compliance with safety and performance standards, which supports hydrogen's sustainable integration into Portugal's energy infrastructure [57].

vii. Portaria no. 109/2024/1: This regulation, published on March 18, 2024, establishes a regime of incentives for the acquisition of zero-emission buses, specifically electric and hydrogen-powered vehicles, including the respective infrastructures for electricity charging or hydrogen refueling. This initiative aims to decarbonize public transport in Portugal, supporting the transition to renewable energy in the transportation sector while enhancing service quality and reducing greenhouse gas emissions. The total allocation for this incentive system is € 90 million euros, reflecting the government's commitment to sustainable public transport as part of the broader Recovery and Resilience Plan (PRR) [58].

viii. Portaria no. 168/2024/1: This regulation, approved in 2024, aims to incentivize the production of renewable hydrogen and other renewable gases in Portugal. It targets mature technologies (with a TRL above 8) and provides a public funding cap of € 15 million per project. The initiative promotes not only the production of renewable hydrogen but also the energy recovery from organic waste components, such as sewage sludge and agricultural and industrial effluents, while excluding plastic waste. This measure aligns with the PRR to enhance energy production, reduce greenhouse gas emissions, and improve energy security [59].

Despite the recent legislative framework in Portugal supporting H_2 implementation, potential challenges and legal obstacles may hinder its full-scale adoption. For instance, integrating hydrogen into the national gas network brings its own set of technical and safety challenges. Existing pipelines may require costly upgrades to safely accommodate hydrogen, posing a potential barrier. Although the EN-H2 sets the goal of incorporating 1 - 5% green hydrogen into natural gas networks by 2025 and 10 - 15 % by 2030, specific regulations on infrastructure adaptation (such as seaports) for hydrogen are still absent, as highlighted by the Energy Services Regulatory Authority [60]

Decree-Law no. 30-A/2022, later expanded by Decree-Law no. 72/2022, was introduced as a set of exceptional measures aimed at simplifying licensing and administrative procedures for renewable energy projects, including hydrogen. However, these measures were only valid for two years. While a new decree (Decree-Law no. 22/2024 [61]) was implemented to address similar goals, it is also set to expire in December 2024. This limited timeframe may deter developers from committing to large-scale projects, as the uncertainty surrounding future regulations can complicate planning and investment decisions. Without permanent measures in place, the hydrogen sector could struggle to scale effectively, hindering progress towards national energy and climate goals, even at seaports.

The economic viability of hydrogen projects is another challenge, despite the incentives provided by Portaria no. 168/2024. Hydrogen infrastructure remains costly, and smaller companies might find it difficult to qualify for public funding due to technical readiness requirements. Financial caps, like the € 15 million limit per project, might also fall short of covering the full expenses of large-scale initiatives. According to Bloomberg New Energy Finance, approximately $ 150 billion (around € 137 billion) in cumulative global public support will be needed by 2030 to halve the costs of producing green hydrogen [62].

Lastly, following the publication of Portaria no. 15/2023 on January 4, 2023, the platform for the auction was only launched in July 2024, with the current phase focusing on final decisions regarding application admissions, initiated in October 2024. This lengthy timeline underscores the challenges within the regulatory framework, potentially delaying the advancement of hydrogen projects and impacting the overall growth of the sector [63].

1.4.2 France

As a reminder, the objectives of decarbonisation fixed by UE directives are the following:

- RED II (2018/2001):
    - 14% of renewable energies in Europe energy mix by 2030;
    - Promoting the use of renewable liquid and gaseous fuels for the transport sector.
- RED III (2023/2413):
    - 42% of renewable energies in Europe energy mix by 2030;
    - 5.5% of Renewable Fuels of Non-Biological Origin (RFNBO) should be used in transport by 2030;
    - 42% of hydrogen production for the industry should be used for Renewable Fuels of Non-Biological Origin (RFNBO) production – 60% by 2035.

European legislation ReFuelEU Maritime, adopted in 2023 and that will be enforced in 2025, covers vessels with a gross tonnage over 5 000 TEU, i.e., 55% of ships calling at European ports, representing 90% of the emissions from the maritime sector. The legislation provides gradual reduction in the greenhouse gas emissions intensity of fuels used by the shipping industry: it should be reduced by 80% by 2050 compared to current benchmark. In addition, 2% of the energy supply of vessels over 5,000 TEU should be RFNBO-based by 2034 if by the end of 2031, less than 1% of RFBNO is used in the maritime energy mix (unless failure to meet this target is due to insufficient availability of RFNBO, uneven distribution or excessive costs).

In France, the National Strategy for the decarbonized hydrogen production (SNH) [64] has been adopted in 2021, in the framework of “France 2030” plan with the target of becoming a leader in green hydrogen production by 2030. Associated public investments account for 7 billion euros, in total, focused on 3 main axes:

- Decarbonisation of the industry towards carbon neutrality by 2050 with 6.5 GW of electrolysis capacity deployed by 2030, i.e. 600 ktH_2/year.
- Development of hydrogen based heavy-duty mobility
- Supporting research, innovation and training development in hydrogen, to build an industrial sector of excellence.

Public investment has already been planned to deploy 1 GW of electrolysis capacity with calls for tender ranging from 150 MW to 600 MW between 2024 and 2026. The national agency ADEME has financed, since 2018, 320 million euros to finance 35 hydrogen ecosystems (including 100 stations and 80 MW of electrolysis capacity).

For the specific case of port infrastructures, "*Stratégie Nationale Portuaire*" (SNP) [65] adopted in 2021 aims at positioning ports as accelerators of the ecological transition, with a special focus on H_2 production. Indeed, because of the density of their activities, port areas are ideal places to accelerate the mass deployment of the hydrogen sector. In return, hydrogen will enable ports to meet their decarbonisation challenges, diversify their economy and boost their attractiveness. One of the objectives of this plan is therefore to ensure clean multi-energy production and supply to provide alternative fuels for ships as part of a national scheme (including H_2 production offer for both industrial and heavy-duty mobility sectors). As a result, French port ecosystem will play a 'pivotal' role for hydrogen massification. H_2 consumption need is estimated between 200 and 600 ktH_2/year by 2030, accounting for 35% to 55% of total national H_2 consumption projection [66]. To accelerate the deployment of decarbonisation in port areas, the national agency ADEME has funded several ZIBAC programs (Zones Industrielles Bas Carbone – *Low carbon industrial areas*) with the ambition of helping industrial areas in their energy transition. Several ports are included in this program and hydrogen projects are planned in those areas.

Finally, DGAMPA (*Direction Générale des affaires maritimes, de la pêche et de l'aquaculture*) has published a decarbonation roadmap for the maritime sector in 2023, the FDR 301 Maritime, in line with the law "Climat et résilience" (Climate and resilience) n°2021-1104 proposing several decarbonation scenarios. They highlight a projected significant need for biofuels for the marine sector of around 15 TWh in 2035 (30 TWh of e-fuels in 2050) which will be partially produced using hydrogen.

The implementation of those ambitious policies is hampered by the lack of a clear regulation framework at a national level. Indeed, although hydrogen has been the subject of a great deal of work at the European level, which has made it possible to clarify the regulatory framework, with the "Hydrogen and decarbonised gases" package, known as the 4th gas package, adopted by the European Parliament and the Council, respectively, on 11 April 2024 and 21 May 2024, its transposition at a national level is not completely defined yet.

In France, public funding is conditioned on the type of hydrogen produced. Hydrogen is defined in two regulation codes: "Code de l'énergie", (*Energy regulation*) defining renewable and low carbon hydrogen and "Code minier" (*Mining regulation*) defining native hydrogen (also known as "white hydrogen"). Renewable hydrogen is defined in Art. L 811-1 of « Code de l'Energie »: « (…) Renewable hydrogen is hydrogen produced either by electrolysis using electricity from renewable energy sources as defined in Article L. 211-2, or by any other technology using exclusively one or more of these same renewable energy sources and not conflicting with other uses allowing their direct recovery. (...) In all cases, its production process emits, per kilogram of hydrogen produced, a quantity of carbon dioxide equivalents less than or equal to a threshold." This threshold has been recently defined in decree on July 1st, 2024 and is set to 3.38 kgCO_2/kgH_2. Low carbon hydrogen is defined in line with European directives (Directive UE 2024/1788 of June 2024) and should reduce carbon footprint by 70% compared to the reference fossil fuel. Although at a European level, grey and white hydrogen are therefore excluded from the energy public funding, France regulation is more open as since 2022, "Code minier" has been updated to add native hydrogen to the list of authorised mining substances.

Although the production of hydrogen is well defined in the regulation, its use and the development of hydrogen project require complex licensing and permitting processes in France. On overview of the current regulations is presented hereafter.

Depending on the characteristics of the hydrogen installation, according to the environmental code "*Code de l'Environnement*", the installation may require ICPE (*Installation Classée Pour l'Environnement*) authorisation:

- **Hydrogen production:** hydrogen production at sea has been excluded from ICPE by decree on July 4th 2024. However, hydrogen production onshore is still covered by ICPE 3240 and require environmental permitting, although most pilot plants have received derogation to this date by showing their low impact on the environment. For higher electrolysis capacity, ICPE 3240 may nonetheless be applied in the future.
- **E-fuel production** is also covered by ICPE 3240 if large quantities of fuel are produced or/if there is an impact of this production on the environment.
- **Hydrogen storage** is covered by ICPE 4715. An Environmental impact assessment is needed if the storage is above 1 000 kgH_2 and an environmental declaration is needed if the mass stored is between 100 kgH_2 and 1 000 kgH_2
- **Hydrogen combustion and e-fuel** distribution is covered by ICPE 2910 and ICPE 1414
- **Hydrogen distribution** is covered by ICPE 1416 and environmental impact assessment is needed if the storage is above 2 kg/day.
- **Hydrogen transport**
  - Transport of H_2 is covered by international regulation regarding transport of dangerous goods "Transport de Matière Dangereuse" (TMD).
  - Transport of H_2 by pipes is also covered by Environmental code and require several authorisations: canalisation with a length above 40km and of external diameter of 800mm are subjected to environmental evaluation. In addition, a danger study shall be performed every 5 years.

In addition, for a hydrogen installation, the implementation of a PPRT "*Plan de Prévention des risques technologiques*", with the subsequent authorisation and studies is required. They include, among other, ATEX regulation with directive 1999/92/CE or ATEX 137 for the protection of workers in explosive atmosphere areas and directive 2014/34/UE for the equipment installed in potential explosive atmosphere areas. Areas with hydrogen are generally classified as hazardous areas.

Finally, the use of hydrogen and/or e-fuel for vessels is still not addressed in the regulation, hampering its use for the navigation:

- For inland waterway navigation, ES-TRIN has been amended to enable the use of alternative fuels for the propulsion such as hydrogen or methanol;
- For ocean-going navigation however, the IMO framework does not take into account hydrogen and alternative fuels. SOLAS and IGF codes are currently being updated to include those fuels, but their circulation is still not authorized to date.

In conclusion, although some legal frameworks have already been planned in France regarding hydrogen production and use as well as for e-fuel, there are still some barriers for the deployment of those projects:

i) Renewable energy planning does not include clear planning on hydrogen production;

ii) Complex licensing & permitting procedures held back hydrogen project development;
iii) Grid capacity and connection issue slow down some projects;
iv) Uncertainty on the final mix of fuels that will be used for maritime transport limit the development of hydrogen and e-fuel projects.

1.4.3 Spain

In Spain, hydrogen regulation is currently in a development and adaptation phase, with no specific legislation exclusively addressing green hydrogen production. The key aspects of the current regulatory framework are presented in this section.

Hydrogen production is regulated under a generic industrial framework, regardless of the production method, which does not differentiate between the various types of hydrogen, such as green, blue, or grey. All forms of hydrogen production are classified as chemical activities, regardless of the production method, storage capacity, or final use of the hydrogen. According to Royal Decree 815/2013 [67], all hydrogen production is subject to the integrated environmental authorization regime. This framework is not well-suited for production through electrolysis, as its environmental impact is significantly different from other industrial hydrogen generation processes.

Hydrogen refueling stations (both on-site and off-site), which are essential for the growth of hydrogen in the mobility sector, operate under various regulations related to compression, storage, and distribution of chemicals, as well as international safety standards. However, the lack of specific procedures for authorizing renewable H_2 production facilities and other necessary infrastructure (such as pipelines) has led to delays in the development of these projects. The technical regulation for the distribution and use of gaseous fuels, approved by Royal Decree 919/2006, sets forth in its complementary technical instruction ITC-ICG 05 the technical requirements and minimum safety measures for designing, constructing, and operating these facilities. Additionally, Regulation (EU) 2023/1804, which replaces Directive 2014/94/EU (AFIR Regulation), governs gaseous fuel installations, including hydrogen, with the aim of expanding the network of refueling and recharging stations for vehicles, trains, ships, and aircraft, promoting sustainable mobility.

Hydrogen storage can be classified into three types. Storage facilities at the production site for subsequent distribution are already regulated by several industrial safety regulations, such as the Pressure Equipment Regulation approved by Royal Decree 2060/2008, and the Chemical Product Storage Regulation approved by Royal Decree 656/2017. For hydrogen fueling stations, as mentioned earlier, regulation is provided through the Technical Regulation for the Distribution and Use of Gaseous Fuels. However, there is currently no specific regulation for hydrogen storage intended to meet the demand for electricity or building heating, such as in the case of fuel cell use.

Hydrogen transport can be classified into three modes, depending on the method used:

- Road transport: regulated by the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) [68];
- Injection into natural gas networks: Regulated by various regulations, such as Royal Decree 949/2001, which establishes access to natural gas facilities, allowing the integration of gases like H_2. Circular 1/2021 of the National Commission for Markets and Competition (CNMC) allows the injection of hydrogen mixed with natural gas, as long as the capacity of the existing infrastructure is respected. Royal Decree 1434/2002 introduces a provisional regime for connecting renewable

gases, such as hydrogen, to the natural gas network, although for direct connections, compliance with the Hydrocarbons Law is required, adding bureaucracy to the process. Royal Decree 445/2023 also imposes the requirement for a simplified environmental assessment for electrolytic hydrogen projects, managed by the Autonomous Communities, which may result in variability in timelines. Furthermore, electrolysis requires administrative concessions under the Water Law, increasing the complexity of the process;

- Exclusive hydrogen networks: currently lacking specific regulations, these networks require a regulatory framework that considers the particularities of hydrogen, such as its effects on materials and the risks associated with leaks.

The lack of specificity in the current legal framework, such as classifying H_2 production as an industrial activity, complicates the implementation of hydrogen projects in Spain. This lack of clarity complicates the process of obtaining permits and installing infrastructure, as such activities are only allowed on land classified as industrial, limiting the deployment of electrolyzers on land classified otherwise.

To overcome these obstacles and ensure the advancement of green hydrogen projects, it is necessary to address challenges in three key pillars, Figure 3:

- *Project development*: encompasses the planning, permits, and infrastructure required to carry out the project. It is crucial to have a suitable location with access to energy and water. However, classifying these activities under the "general industrial" category delays the necessary permits;
- *Access to renewable energy*: The production of green hydrogen requires a constant supply of renewable energy. Currently, in Spain and other European countries, there is saturation in the energy grid, complicating the process of obtaining interconnection permits, highlighting the need for regulatory updates;
- *End customer*: The project's viability also requires securing hydrogen demand through long-term hydrogen purchase agreements (HPAs) [69]. However, price competitiveness against grey hydrogen presents difficulties, as the latter is the most economical option.

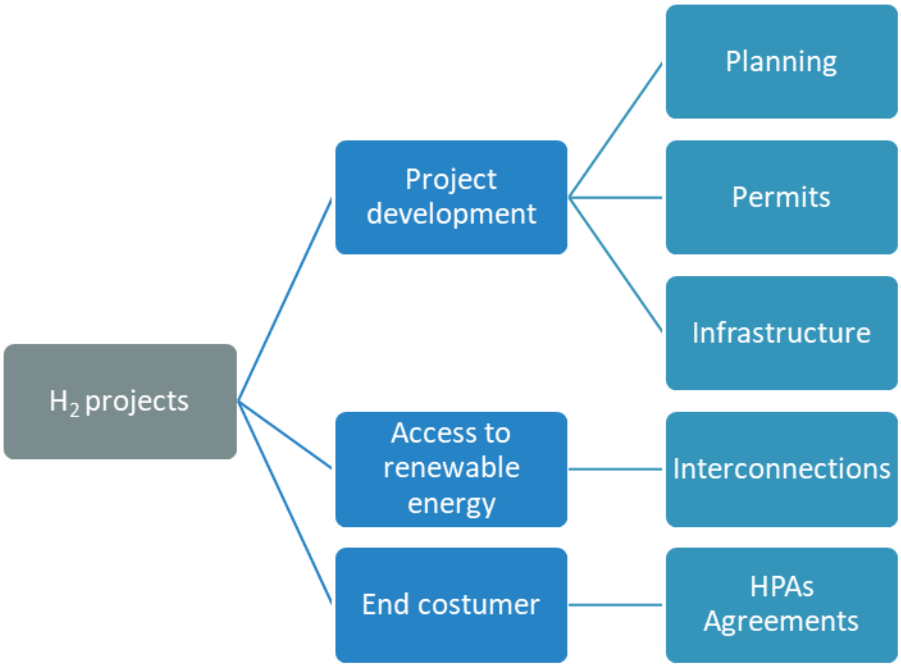

Figure 3. Key pillars of renewable hydrogen projects.

In summary, the development of green hydrogen projects in Spain faces significant challenges related to the lack of specific regulations and regulatory barriers that affect the issuance of permits, access to the energy grid, and the formalization of purchase agreements. Overcoming these bottlenecks requires regulatory updates and simplification of administrative procedures, ensuring a framework that allows efficient energy interconnection and certainty in hydrogen demand.

Below are additional regulations, laws, and decrees involved in the regulation of H_2 in Spain [70]:

i. **National Hydrogen Strategy 2020:** A document that establishes the goals and actions for the development of renewable hydrogen in Spain, promoting its production, distribution, and use across different sectors. It aims to contribute to the energy transition and emission reduction;

ii. **Directive (EU) 2018/2001 on renewable energy:** This directive establishes a framework to promote the use of renewable energy within the EU, including hydrogen as a form of energy storage and carrier**;**

iii. **Regulation (EU) 2020/852 on the sustainability taxonomy:** Provides criteria to classify sustainable economic activities, including hydrogen production. It facilitates investment in clean energy technologies;

iv. **Law 21/2013 of December 9, on environmental assessment:** Regulates the environmental assessment procedures for projects, including hydrogen production, ensuring that environmental impacts are analyzed**;**

v. **Royal Decree 244/2019 of April 5:** Regulates access and connection to electricity transmission networks, establishing procedures for connecting hydrogen production facilities to the power grid, crucial for facilitating their integration**;**

vi. **Regulations on hydrogen safety installations:** Includes various regulations and technical standards that establish safety requirements for hydrogen production, storage, and transport**;**

vii. **Directive (EU) 2019/944 on the internal electricity market:** Promotes the integration of clean technologies, including hydrogen, into the electricity market, fostering decarbonization and efficient use of energy resources;

viii. **Regulation (EU) 2021/241 establishing the recovery and resilience mechanism:** Includes funding for renewable energy projects, including those related to hydrogen, as part of the post-COVID-19 economic recovery;

ix. **Law 24/2013 of December 26, on the electricity sector:** Establishes the regulatory framework for the electricity sector in Spain, including provisions for the production of electricity from renewable sources, such as hydrogen;

x. **Regulation (EU) 2023/1804:** Replaces Directive 2014/94/EU (AFIR Regulation) and aims to expand the network of refueling and recharging stations for vehicles, trains, ships, and aircraft, promoting sustainable mobility;

xi. **Royal Decree 815/2013:** Industrial emissions regulation and development of Law 16/2002 of July 1, on integrated pollution prevention and control**.**

1.4.4 Ireland

i. **Issues affecting pre-deployment and rollout of large-scale hydrogen economy:**

Ireland, as previously analyzed by the AA's 2020 SEAFUEL project, assumed a low-risk, late adopter position to H2 technologies. This followed a similar stance taken by the country to large-scale offshore wind deployment, as one of its measures to recover from the 2008-2011 financial crisis. However, the nation recognized the need to accelerate their decarbonization efforts to achieve national and European climate targets and subsequently released the Climate Action Plan (CAP) in 2019. The CAP set goals to increase renewable penetration within Ireland's electrical grid to 70% by 2030 by favoring the deployment of intermittent renewable technologies such as wind and solar. This, alongside the country's existing high levels of curtailment (8.5% of all wind energy equivalent to 1,280 GWh wasted in 2022 [71]) helped to increase interest in hydrogen as an energy vector within the geography. Hydrogen's profile was further raised following the release of the National Development Plan (NDP – 2021) which was expected to further exacerbate dispatch down issues by expanding penetration goals to 80% and targeting 15.5GW of deployed wind and solar capacity within this timeframe.

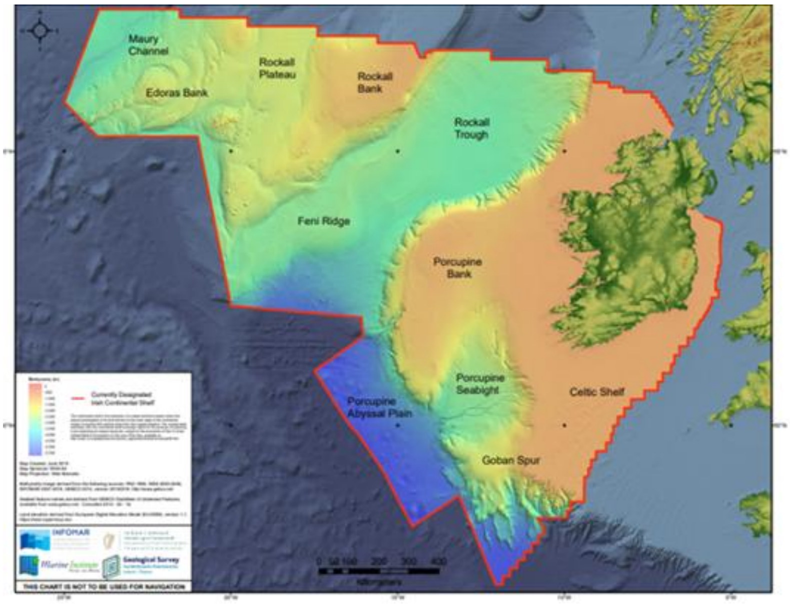

Figure 4. Ireland's total marine area of 880,000 km^2 is ten times greater than the country's land area. It has some of the highest average wind speeds in the EU and relatively shallow water making it ideal for offshore technologies.

These developments, alongside constant pressure from local hydrogen projects (Gencomm, SEAFUEL, HUGE), ever-growing industry/community bodies (Hydrogen Ireland, Community Hydrogen Forum), as well as ongoing policy development and high-level partnerships at the European level (Declaration of Intent between German & Irish governments [72]) have led to the release of Ireland's National Hydrogen Strategy (NHS) [73]. The document sets out the country's long-term ambition to become a net-exporter of renewable hydrogen by prioritizing its offshore potential, and includes interim goals to: establish 2 GW of offshore wind for hydrogen production by 2030; encourage the development of clusters around existing industrial activities, and meet European RFNBO/AFI mandates within the mobility sector. However, despite the publication of this document, there are several serious potential barriers that will prevent attainment of these goals.

The most notable include a general lack of legislation and regulation pertaining to hydrogen, its interaction with renewable technologies, and the wider energy system. Due to Ireland's late adopter position, the Irish government has been slow to formally enact Statutory Instruments (SI) relating to hydrogen. The NHS admits this saying 'There are several gaps in terms of regulations, licensing, and permitting across the entire hydrogen value chain'. This has prevented stakeholders from developing large projects with the confidence that activities will continue to adhere to future SIs, leaving just a handful of publicly funded small-scale demonstrations locally to draw knowledge from. Instead, the Irish government will be forced to look further afield to take learnings from other geographies and their approaches to large-scale deployment to enable their 2030 goals. This includes topics such as large-scale hydrogen storage onshore, offshore, and within geological sites; hydrogen pipelines; low-carbon hydrogen standards, amongst other areas. It is expected that Ireland, which operates as a single energy system across the island, will seek to align to European standards, as this is likely to be its largest potential export market, as well as the proximally located UK market. Reviews are expected to be completed by 2026-2028, leaving a tight development timeline for prospective projects to meet the NHS' 2GW target.

ii. SH2AMROCK, An Irish Deployment Example:

Hydrogen Valleys have become Europe's go-to mechanism to efficiently navigate the initialization of hydrogen sectors within nascent geographies. This approach has proved successful within a variety of locations including those with little industrial gas history such as the island of Mallorca via the Green Hysland project. Ireland is attempting to replicate this methodology within the SH2AMROCK project - a valley combining production, distribution, and unique local end-uses centred around Galway. However, the project, which was approved for funding by the European commission in 2023, is struggling to gain deployment momentum partially due to the lack of regulatory framework. This issue has not been as widespread in locations where national authorities and codes and standards agencies have been engaged directly within valley activities as exhibited in HEAVENN in the Netherlands. Increased clarity in this area is crucial for infrastructure owners and operators across value chain segments to provide long-term investment confidence. Without this, SH2AMROCK is to likely experience delays, and Ireland will miss vital deployment windows to realise its 2030 targets, and potentially harm its long-term sector prospects.

- Offshore wind development uncertainty and licensing delays**:** in 2021, Ireland passed the Maritime Area Planning Act (the MAP act). This was a complete overhaul of the consenting and planning permission procedures for offshore renewable energy (ORE) expansion, overseen by the new Maritime Area Regulatory Authority (MARA). MARA has the power to grant Maritime Area Consents (MACs), which are required before applying for a development permission. This was designed to speed up the consenting process for offshore sites which at that point regularly waited 18 months to obtain licenses [74]. Following this, Ireland then released the first of its Designated Maritime Area Plan (DMAP) drafts covering the south coast of the island. This is a spatial plan that designates marine areas specifically for offshore renewable energy development in line with the EU's Maritime Spatial Planning Directive. Introduced alongside this plan was a requirement for all ORE sites to be built in DMAP defined territories; a significant rule change that confirmed Ireland's shift from a project/developer-led private process to a public government-led auction-based system. Throughout this period of change, many leading offshore wind projects across the country failed to maintain momentum. This has resulted in significant delays amongst conventional large-scale sites, such as SSE's Arklow Bank Wind Park from 2025 to 2028 [75], with many novel offshore wind-to-hydrogen locations ceasing development altogether. The sector must now have a period of regulatory stability if it is to realize the government's net-zero goals with relation to all areas of ORE. The Irish government has released a 2024 framework document for Offshore Renewable Energy (ORE), detailing their overall strategy in an attempt to bring the market long-term clarity to their intentions.

- Port development and skills infrastructure must keep pace**:** one of the most crucial areas to ensure the scale-up of ORE is ports. These locations will not only behave as energy landing terminals for cables and pipelines, but also as construction and logistics hubs for the deployment of turbines and platforms on the water in the first place. This requires a coalescence of cheap land availability, specialized expertise, grid accessibility, and proximal energy end-users. In 2022, the National Ports Study [76] found that Belfast Harbour was the only port across the island of Ireland ready to deploy offshore wind turbines. According to a recent roadmap published by the Sustainable Energy Authority of Ireland (SEAI), this port can only deploy 40 turbines a year which, at an ambitious 17 MW per turbine, would still fall well short of Ireland's 5 GW goal [77]. Thus, the development of ports is a major bottleneck for the development of ORE including hydrogen. As part of this, Ireland will also need to take an active role in developing the training infrastructure required to address current skills shortages experienced across the whole of the ORE sector [78]. This includes recognized needs for: senior and middle management, electrical, engineering, qualified offshore operators, health and safety and maritime expertise, among others. Shortages are currently forecasted across all project phases (from development and project management, manufacturing, deployment, commissioning and the operations, maintenance and service phase) and without adequate action, spearheaded by the establishment of a national funded skills development plan, deployment will be negatively impacted.

Hydrogen is increasingly seen as a critical energy carrier for the future, particularly in achieving ambitious decarbonization targets. However, as seen in this report, its large-scale adoption faces substantial supply chain challenges on both the production and end-use sides. While technologies such as electrolysis, storage, and fuel cell applications have advanced considerably, the policy frameworks necessary to scale these technologies lag behind, hindering progress.

The successful implementation of hydrogen as an energy carrier at seaports depends on addressing key social challenges and barriers, including public perception, stakeholder engagement, workforce transition, regulatory frameworks, and environmental justice. By fostering transparent communication, ensuring inclusive stakeholder participation, promoting job retraining programs, and advocating for clear regulations, the maritime sector can effectively navigate these challenges. Seaports have the potential to lead the transition to a hydrogen-based energy system, contributing to a decarbonized, sustainable future.

2 Mitigation Measures and Solutions

This chapter refers to the mitigation measures and solutions to address challenges and barriers for the implementation of hydrogen-based infrastructures in the ports. Table 4 describes suggested technical mitigation measures that should be considered when addressing various challenges and barriers associated with hydrogen and other renewable energy sources.

Table 4. Recommended mitigation measure: technical level.

Typology	Main Bottlenecks	Recommended Mitigation Measures
	Technical	
Marine Renewable Energy	Technical standardization for further maturity	Incentives and focused investment into the most promising technologies, rather than dispersive investments
	Space allocation in ports' vicinity	Clear identification of available space and viable deployment capacities at each port within the AA area partaking in H_2 projects
	Installed capacity	Establishment of more realistic and consistent milestones and evaluation of effective limits of installed capacity at ports, considering all involved variables
	Lower technological maturity of wave energy	Directed incentives towards the development and deployment, at sea, of high TRL-TPL concepts
	WECs require more devices that occupy a larger marine space which could result in conflict/restrictions	Focus on establishing suitable deployment areas for WECs, promoting agreements between stakeholders and co-location opportunities (*e.g.*, Portugal's ORE areas)
	Uncertainty related to design standardization	Incentives and focused investment into the most promising technologies, rather than dispersive investments, supported by additional R&D efforts
Energy carriers	Extremely low temperatures and high pressures are required, necessitating robust safety measures and adequate space	Convert hydrogen to e-fuels for easier storage and transport. E-fuels, such as synthetic methane or methanol, can be stored using existing infrastructure, alleviating challenges associated with the extreme temperatures and high pressures required for hydrogen storage. This enhances energy density and leverages current fuel distribution networks.
	Dependence on critical and strategic raw materials like platinum, iridium, and titanium in hydrogen production and purification can lead to supply chain vulnerabilities and higher costs	To reduce reliance on critical materials, future development should prioritize (i) enhancing catalytic efficiency to lower material loadings, (ii) increasing recyclability and reuse, (iii) optimizing electrolyzer design to minimize critical material use, and (iv) exploring alternative H_2 production technologies that employ more sustainable and abundant resources (*e.g.*, methane decomposition).

	Due to hydrogen's small molecular size, it can diffuse through storage containers	Storage can be improved by using advanced barrier materials (*e.g.*, multilayered polyethylene or polyimides and metal hydride coatings), multi-layered tanks, or converting hydrogen to e-fuels, which are easier to store and handle safely.
	Hydrogen has a low volumetric energy density	A problem that may be circumvented by converting it into liquid carriers
	Methanol's toxicity to humans	To mitigate methanol's toxicity risk, safety protocols can leverage established industrial practices developed over decades of use across various sectors. Proper handling, storage, and personal protective equipment (PPE) are critical, along with robust training and emergency procedures, to ensure safe usage.
	Conversion of CO_2 to methanol is usually limited to 15-25%.	It is essential to develop more efficient catalysts alongside innovative reactor designs. These advanced reactors can be engineered to facilitate the *in situ* removal of water produced as a by-product, effectively shifting the equilibrium of the reaction toward methanol production.
	The combustion of methanol results in CO_2 emissions, contributing to greenhouse gas emissions.	To establish methanol as a genuinely sustainable energy vector, capturing the CO_2 generated during combustion is crucial
	Ammonia synthesis requires high pressures and temperatures, demanding significant energy.	To address the efficiency of ammonia synthesis, it is essential to develop methods that operate under milder reaction conditions compared to the traditional Haber-Bosch process. Innovative production techniques to be explored include photocatalytic and electrocatalytic processes.
	AEM is still under development, to optimize features such as membrane stability and robustness, while SOEC technology still faces problems regarding long-term system durability	Incremental progress may be a viable pathway to overcome the aforementioned problems, particularly those of the two most used types of electrolyzers (*i.e*, PEM and conventional alkaline electrolyzers).
Seaports and External Entities	Using liquid Hydrogen for ships' propulsion or even trucks, cranes, and reach stackers requires important modifications of this equipment	Develop and promote retrofitting kits and standard conversion protocols for ships, trucks, cranes, and reach stackers. Both positive (e.g., fee discounts and retrofitting financing) and negative (e.g., emission and refueling taxes) mechanisms can be considered to adjust the shipping sector's economic incentives accordingly. An analogy can be established with the current carbon credits and taxes system, for instance. Incentivize R&D for cost-effective hydrogen-compatible equipment with European public and private funding.

		Create pilot programs in ports to test and demonstrate hydrogen-powered machinery to lower technical adoption barriers, such as limited numbers of tugboats, trucks or cranes.
	The large spaces required to install H_2 production plants while ports generally lack space to develop their activities	Explore vertical infrastructure, hinterland logistical networks/storage sites and modular hydrogen production units to maximize space efficiency. Collaborate with nearby industrial zones or logistics hubs for off-site hydrogen production and transport back to ports. Promote digital twin technologies for optimal space planning and layout designs in congested ports.
	The supply-chain of new energies	Given the variety of contexts, port authorities should prepare supply-chain strategic plans for energy carrier implementation at their seaports. As done in this report, specific bottlenecks and challenges should be identified and addressed. When future demand is highly uncertain, consider incremental infrastructure development based on market needs. Prioritize renewable energy sources from European companies/industries, particularly those related to solar, (offshore) wind, wave and tidal energy. The same applies for electrolyser supply, to ensure European autonomy and resilience while bolstering seaport and marine economy. Identify potential mismatches between energy supply and demand for each region, as well as electrical grid congestion risks. Invest in expanding and diversifying the energy mix and grid supply options.
	Develop Infrastructure for alternative fuel generation	Develop public-private partnerships to co-finance infrastructure development for hydrogen supply chains. improve forecasting and accelerate integrated planning to identify realistic hydrogen infrastructure needs, avoiding overinvestments and reducing costs related to under-recovery risks. Conduct feasibility studies to identify suitable sites and scalable technologies for hydrogen generation and storage. The resulting data should be shared with stakeholders and publicly available (e.g., online platforms and layered geoportals). Leverage existing LNG infrastructure for partial integration into the hydrogen supply chain where feasible. Also consider blending case studies with increasing share of hydrogen over time.

	Global standardization for integration and Interoperability	Work with international bodies (e.g., IMO, ISO), in particular European ones, to establish universal hydrogen standards for maritime applications whilst accounting for the unique features of each seaport. Foster collaborations among countries and ports for aligned technical and safety protocols, as is being done in the HYDEA project. Develop open data-sharing platforms and public industry-standards to harmonize operational standards globally.
	The current lack of available models of vehicles and machinery designed to run on hydrogen can hinder immediate adoption	Provide incentives for manufacturers to design and produce hydrogen-powered vehicles and port machinery, as currently seen for lithium-batteries in electric vehicles. Partner with innovators and startups to accelerate prototype development and testing. Promote early adopter initiatives in key ports to scale demand for hydrogen-compatible equipment.

Table 5 describes suggested economic mitigation measures that should be considered when addressing various challenges and barriers associated with hydrogen and other renewable energy sources.

Table 5. Recommended mitigation measure: economic level.

Typology	Main Bottlenecks	Recommended Mitigation Measures
	Economic	
Marine Renewable Energy	High investment cost of building hydrogen-powered ships / retrofitting existing ones	Implementation of economic incentives towards OPS, "cold ironing" and other retrofitting measures, both positive (*e.g.*, discounted electricity prices) and negative (*e.g.*, emissions taxes for CO_2, NO_x, SO_x, etc.)
	Lack of financial incentives to facilitate the adoption of new propulsion technologies for vessels	Development of new financial incentives to facilitate the adoption of cleaner propulsion technologies and reduce emissions in maritime transport.
	High prices of green hydrogen	Scaling up of green hydrogen supported by cost-effective MRE/ORE
	Offshore wind cable damage, followed by turbine failure as the second major cause	Increment investments and efforts on additional R&D on sustainable and resilient offshore wind cable development and deployment
	Wave energy has seen significant investments over the past decades, but the LCoE remains too high for sizeable commercial projects to take shape	Incentives and focused investment into the most promising technologies (high TRL-TPL and low LCoE), rather than dispersive investments, supported by additional R&D efforts. Promotion of sea trials to demonstrate and scale-up promising WEC technologies

	Tidal energy costs remain high compared to other sources of renewable energy	Keep supporting tidal energy development and deployment to build on experience and feedback, improve reliability, efficiency and gradually check the milestones leading to industrial scale
	A limited number of suitable locations for tidal energy generation	Prioritize investments according to local availability of resource and local cost of energy production (i.e. islands, offgrid areas) – wind, wave and tidal, supported by onshore renewables
Energy Carriers	The cost of electricity required for Hydrogen production	Investing in solar, wind and marine energy projects to establish dedicated renewable power supplies for electrolysis facilities is essential to lowering electricity costs for hydrogen production.
	PEM electrolyzers require higher investments due to the materials they contain	To address the higher costs associated with PEM electrolyzers, a practical alternative is to leverage alkaline electrolyzers, which typically have lower upfront costs and simpler designs. Between 2014 and 2019, the cost of alkaline systems dropped significantly (40% when manufactured in Europe and North America), with the potential for continued cost reductions as manufacturing scales up. However, further development is needed to improve the efficiency and adaptability of alkaline electrolyzers, so they can match the performance levels of PEM systems.
	Using H_2 as an energy carrier may incur additional costs related to transportation, particularly due to its low energy density	Developing dedicated supply chains is proposed to mitigate the H_2 transportation cost. This could involve creating clusters of industrial customers supplied by specialized pipeline networks that combine wind-, solar- and marine-powered electrolyzers and large-scale geological storage facilities to buffer supply fluctuations. Such an approach could help achieve competitive delivered costs for green hydrogen, estimated at *ca.* € 1.9 kg^{-1} by 2030 and € 0.9 kg^{-1} by 2050 in regions like Western Europe.
	The cost of green ammonia is six times more than the non-green ammonia	Improving the efficiency of ammonia synthesis by developing innovative production methods – like photocatalytic and electrocatalytic processes – can lower production costs and make green ammonia more competitive. Additionally, exploring new catalysts and optimizing current processes can help bridge the cost gap between green and conventional ammonia production.
	With respect to methanol, costs arise from the low efficiency of the reaction that forms methanol	It is crucial to focus on enhancing reaction efficiencies to address the economic challenges associated with methanol production. Developing advanced catalysts and innovative reactor designs can significantly improve the overall yield of methanol.

	The separation of methanol from the side-produced water requires distillers, which are expensive and energy-consuming.	Alternative separation processes can be explored. One promising approach is the use of carbon molecular sieve membranes (CMSM), which can effectively separate methanol from water based on molecular size and shape. This method is generally less energy-intensive and can significantly reduce operational costs compared to traditional distillation methods.
	Electrolyzer manufacturing is another major bottleneck in the hydrogen economy	Scaling up electrolyzer production capacities and enhancing supply chain efficiency for critical materials is vital. Investing in research and development can foster innovations that lower costs and boost production rates. Additionally, improving recycling methods for critical minerals ensures a sustainable supply chain. Exploring alternative materials and collaborating with existing manufacturers can further streamline production processes.
Seaports and External Entities	High investment cost of building hydrogen-powered ships or re-converting and/or retrofitting existing ships	Introduce subsidies, tax breaks, or low-interest loans for early hydrogen adopters in the shipping and logistics sectors. Foster international collaboration to pool resources for large-scale hydrogen projects, reducing per-unit costs. Encourage cost-sharing agreements between ports, shipping companies, and governments to spread the financial burden.
	The price of green hydrogen for deployment as a fuel, even when compared to other energy carriers like methanol	Accelerate electrolyzer deployment and decarbonization of the electricity sector to increase renewable hydrogen's cost competitiveness. Scale up renewable energy production to reduce the cost of green hydrogen through economies of scale. Implement carbon pricing mechanisms to make hydrogen more competitive, especially when compared to fossil fuels. Support research into cost-reducing technologies for hydrogen production, such as advanced electrolysis methods.
	Lack of financial incentives to facilitate the adoption of new propulsion technologies for vessels	Development of new financial incentives to facilitate the adoption of cleaner propulsion technologies and reduce emissions in maritime transport.
	Define the most cost-effective means of distribution for each region and hinterland without compromising the standardization and	Conduct regional studies to optimize hydrogen distribution networks (e.g., pipelines, tankers) and assess the most cost-effective solutions that also mitigate external dependencies and supply-chain disruption risks.

	compatibility of the transport networks	Consider the repurposing of gas networks for hydrogen to minimize costs, while not overlooking the potential impacts on the broader gas sector. Promote investments in multi-modal transportation solutions that integrate hydrogen seamlessly into existing networks. Work with stakeholders to establish standards for transport containers and infrastructure to ensure compatibility across regions

Table 6 describes suggested social mitigation measures that should be considered when addressing various challenges and barriers associated with hydrogen and other renewable energy sources.

Table 6. Recommended mitigation measure: social level.

Typology	Main Bottlenecks	Recommended Mitigation Measures
	Social	
Marine Renewable Energy	Offshore wind turbines, like their mainland counterparts, are susceptible to the "Not In My BackYard" (or NIMBY) mentality	Transparency, consistency, economic viability, and reliability will be crucial for a supported deployment of offshore wind. Marine studies on the actual impacts of offshore wind onto local habitats, ecosystems and species.
	Wave energy is not as mature or as established, which corresponds to a lower degree of awareness in local communities	Educational and awareness raising efforts alongside local communities (*e.g.*, workshops, webinars, "open-days/labs", public sessions, etc.)
Energy Carriers	Lack of public understanding and awareness	Launch public education campaigns to demystify hydrogen, focusing on its benefits, safety, and environmental impact. Implement transparent communication strategies that explain safety protocols, risk management systems, and emergency response plans to mitigate concerns.
	Lack of collaboration and coordination Competing interests	Foster inclusive stakeholder collaboration by establishing dialogue forums to align interests and create integrated hydrogen strategies. Involve local communities and stakeholders in decision-making processes to ensure that concerns are heard and addressed early in the planning stages.
	Job displacement	Develop job retraining and reskilling programs to help workers transition to roles in the hydrogen economy, in partnership with educational institutions.
	High investment costs	Promote transparency in economic planning and highlight the long-term job creation potential and economic benefits of hydrogen projects to gain public and worker support.

	Lack of coherent regulations Inconsistent government policies	Advocate for the development of clear and comprehensive regulations that cover hydrogen production, storage, and transportation to provide certainty for stakeholders. Governments should establish financial incentives and support mechanisms to encourage investment in hydrogen infrastructure.
	Disruptions during construction Integration with existing systems	Engage local communities in the infrastructure planning process and address their concerns about disruptions through transparent dialogue and mitigation strategies. Ensure that hydrogen infrastructure is designed to complement existing port operations, minimizing disruptions to logistics and supply chains
	Equitable distribution of benefits Environmental impact	Conduct thorough environmental and social impact assessments to address community concerns and ensure that hydrogen projects promote sustainability and equity. Prioritize environmental justice by ensuring that the benefits of hydrogen, such as cleaner air and job creation, are distributed equitably among all stakeholders.
	Safety concerns	Promoting awareness and education about the benefits and safety of hydrogen can further enhance social acceptance and participation in the transition towards a cleaner port environment.
Seaports and external entities	Public awareness and acceptance	Increasing public awareness and acceptance of renewable energy initiatives through education, outreach programs, and effective communication strategies to garner support and overcome potential resistance.
	Environmental impact assessment	Conducting comprehensive environmental impact assessments to minimize any potential negative effects of energy transition initiatives on the marine ecosystem and surrounding areas.
	Knowledge and skills	Promoting capacity building, knowledge sharing, and skill development among industry professionals and workers to enable the effective implementation and maintenance of renewable energy systems. Specialized training and education for vessel and port service personnel in the use and handling of new fuels, clean technologies and renewable energy
	Stakeholder engagement	Engaging and involving various stakeholders, including port authorities, businesses, local communities, and government agencies, to foster collaboration and ensure the successful implementation of sustainable energy solutions.

		Encouragement of collaboration among industry stakeholders to drive research and development of sustainable energy solutions. Encouragement of research and development into emerging technologies, such as the use of green ammonia or methanol as alternative fuels.
	Safety	Guarantee the safety of operations in hydrogen production, supply and use to avoid workplace accidents or accidents in port areas that may affect surrounding populations.

Table 7Table 6 describes the suggested legislation "mitigation measures" that should be considered when addressing various challenges and barriers associated with hydrogen and other renewable energy sources.

Table 7. Recommended mitigation measure: legislation level.

Typology	Main Bottlenecks	Recommended Mitigation Measures
Legislation		
France	The implementation of ambitious policies is hampered by the lack of a clear regulation framework at a national level	Transpose the EU (2024) hydrogen and decarbonized gas laws into national legislation and implement the directives, accordingly. This is valid for all AA regions. Clear and thoughtful mid-/long-term objectives at regional and national scale, combined with supportive/facilitating and incentive regulation are necessary to lift the regulation-related risks.
	The use of hydrogen and e-fuel for vessels is still not addressed in the regulation, hampering its use for navigation	Feedback on pilots and demonstrators to showcase the potential of e-fuel vessels and point out the regulation difficulties that should be addressed in priority
	Complex licensing & permitting procedures	Simplification and clarification of bureaucratic processes through development of dedicated one-stop-shop procedure is recommended
	Uncertainty on the final mix of fuels that will be used for maritime transport	One single type of fuel is unlikely in ports, studies on scale of compatibility between the different fuels from safety, regulation, economical, land space etc. aspects should contribute to feed the choice of final mix of fuels. Provide market certainty over the role of non-renewable, low-carbon hydrogen.
Ireland	Lack of hydrogen-specific legislation and regulation	Development of standards and regulations for hydrogen production, storage, distribution, and usage
	Currently no policy support or subsidy for hydrogen projects	Fast-tracking of the Hydrogen Demonstration Fund set out in the government's hydrogen strategy

	Low readiness of port infrastructure for offshore renewables deployment and hydrogen	Urgent government plan to address current lack of port facilities for offshore wind and hydrogen development, including significant funding and investment required
	Planning delays	Streamlining of the planning process for renewable energy projects and adequate resourcing and training of the national planning authority ('An Bord Pleanála' – *The Planning Board* is currently undergoing a restructuring which will see it replaced by 'An Coimisiún Pleanála' - *The Planning Commission*)
Portugal	Policy and regulation uncertainty	Clarification and fixing of milestones for the upcoming decades, aiming at legislative stability and realism of the proposed objectives. Consolidation of a national strategy that encompasses all involved stakeholders.
	Complex and lengthy licensing processes	Simplification of bureaucratic processes through digitalization, legislative adjustments and ease-of-business promotion, whilst respecting existing requirements (*e.g.,* conserve marine areas)
	Lack of specificity in the current legal framework	Consolidate the national strategy for energy transition with key stakeholders, from MRE to energy carriers at the main ports of Portugal. Disseminate and execute the foreseen activities and investments, as listed by DGEG [79]
	Lack of transparency/corruption to policy changes with alternating governments	Transparent communication and participatory planning processes can help address concerns and build support for renewable energy initiatives. The definition of the PAER, for instance, implied public engagement through the "Participa.pt" platform
Spain	No specific legislation exclusively addressing green hydrogen production and storage	Overcoming these bottlenecks requires regulatory updates and simplification of administrative procedures, ensuring a framework that allows efficient energy interconnection and certainty in hydrogen demand
	The lack of specific procedures for authorizing renewable H_2 production facilities and other necessary infrastructure	
	The integrated environmental authorization regime is not well-suited for production through electrolysis	

3 Conclusions

This deliverable identifies key bottlenecks in the energy transition decision-making phase at seaports, particularly related to MRE, hydrogen and related energy carriers. These challenges are presented at 4 levels: social, technical, legal, and economic. This conclusion summarizes these challenges and barriers based on these levels as follows:

Technical challenges and barriers

Hydrogen clearly faces many obstacles in these 4 levels. To explore these issues, the hydrogen value chain was divided into 3 categories (marine renewable energy, energy carriers, and seaports and external entities).

- Regarding MRE, technological standardization is needed for offshore wind, mainly so for floating technologies, wave and tidal energy to mature. Commercial standardization, investment channelling, and economies of scale in wave energy have been difficult to obtain, as well as a significant number of successful commercial case studies at sea.
- Concerning energy carriers, due to its low temperatures and high pressures, hydrogen storage systems like compressed gas tanks and liquid hydrogen tanks require robust safety precautions and ample space. As mentioned, H_2 storage is challenging; Hydrogen diffuses through storage containers, even those designed for other gases, due to its small molecule size. This is the same for pipelines.
- On the other hand, the stability of direct CO_2 hydrogenation catalysts is a problem for methanol. Another issue is that CO_2 to methanol conversion is currently restricted to 15-25%. This low conversion rate affects the process's economic viability, energy balance, and efficiency when using CO_2 as a feedstock for methanol synthesis. Methanol's toxicity to humans through ingestion, inhalation, or skin absorption is another problem. Due to methanol's flammability, handling and storage must be strictly controlled to avoid accidents.
- Ammonia synthesis has its own challenges as well, especially in the Haber-Bosch (HB) process, which demands high pressures and temperatures and plenty of energy, usually from fossil fuels. Toxicity is an equally pertinent issue to consider, from both safety and handling perspectives.
- Ports are essential hubs for maritime-related economic activities, affecting the environment and developing local communities. Port operations can set a sustainability standard by investing in energy carriers like hydrogen, energy efficiency, renewable energy, and electrification. To attain these goals, various problems must be addressed: major technical obstacles to overcome include H_2 engine or fuel applicability for logistics and transport equipment at and near ports; large land expanses are required to establish H_2 production plants while ports lack space to grow; power for long and medium distances that is both cost-effective and viable, in terms of electric grid capacity and transport networks; new energy supply chain and interdependencies; build new fuel infrastructure and supporting equipment, from generators to electrolizers; global integration and interoperability standardization, to avoid congestion and conflict of technologies. In essence, the fundamental problem is adapting and building new infrastructure to generate, store, and distribute alternate fuels. The limited supply and demand of hydrogen-powered vehicles, machinery and supply stations can also slow this adoption.

Economic challenges and barriers

- Cable damage accounted for 53% of offshore wind claims by value from 2014 to 2020, followed by turbine failure at 20%. Fluctuations in prices in global markets for raw materials, components, and alternative energy sources can pose investment risks, alongside pressing competition for qualified human resources and access to energy transfer/transport networks. As offshore wind increases and moves further offshore, investors and stakeholders may view it as a risky investment with uncertain returns. Sea trial data is limited, adding uncertainty that might discourage investment. Tidal and wave energy costs are greater than other renewables and the lack of adequate tidal/wave energy-producing sites is critical.

- The cost of power to produce green hydrogen is a major economic barrier. Alkaline electrolyzers use cheap steel and nickel alloys, making them more affordable. PEM electrolyzers cost more since they use iridium. Apart from the production costs, transporting H_2 as an energy carrier may incur additional costs due to its low energy density.
- On the other hand, a ton of green ammonia costs 720–1400 USD, six times more than non-green ammonia, making the transition expensive.
- The current low efficiency of the methanol reaction creates additional costs. Distillers are expensive and energy-intensive for separating methanol from side-produced water.
- Overcoming high initial costs and securing a consistent supply of green hydrogen are crucial to economic viability. Building hydrogen-powered ships or modifying existing ones is expensive. Green hydrogen fuel price is higher, even compared to methanol. Consistent and oriented financial aid for ports using renewable energies, particularly MRE, to become energy self-sufficient is required.

Social challenges and barriers

- Offshore wind turbines, like their mainland counterparts, are susceptible to the “Not In My BackYard” mentality. There is a visual impact on coastal communities (albeit reduced further away from the shoreline) and competition with other maritime space users.
- Wave energy is less developed than offshore wind, therefore community members are less aware of it. This will require additional research, policy, and stakeholder education. The tidal energy sector has had few successes (Hydroquest, Eel Energy) and numerous failures (Open Hydro, Sabella, etc.). Tidal energy is a risky investment with little employment impact.
- Hydrogen is flammable, thus local communities and port workers especially non-specialists, are concerned about its storage and transportation. Misunderstanding energy carrier risks and lack of collaboration and coordination can lead to public resistance and reduced support from stakeholders, investors, and politicians.
- Misinformation, poor community engagement, and insufficient awareness raising can undermine seaport hydrogen technology development. The green energy transition means the closure of fossil fuel-based enterprises, which can eliminate certain jobs. Without re-skilling and training programs to adapt affected workers to new H_2 integration functions in seaports, there is a risk of human potential loss and widespread discontent against this implementation process from a cost-benefit and social standpoint.

Legal challenges and barriers

This subtopic was analysed by country to identify the distinct challenges encountered by each partner in the renewable energy transition. Additionally, it aimed to assess the existing regulations and policies related to the application of hydrogen in ports. The gathered data reveals certain uncertainties, limitations, and a deficiency in regulation regarding the production, transportation, storage, and distribution of hydrogen.

Constant fluctuations in regulations and policies, in part attributed to changing policymakers and governments, can lead to ambiguity for investors and project developers. It is essential to align policies and regulations across borders to promote the advancement of these interconnections. Neglecting this will significantly limit the intra and interconnectivity of the AA region, obstructing supply and distribution chains, and may lead to legal complications among the AA partners, which undermines the essential cooperation required for these initiatives. Clear, transversal (yet adaptable) and consistent (in time) legislation is pivotal, at this stage, as there is a definitive risk of bureaucratic quagmires stalling energy carrier deployment at seaports.

All of these bottlenecks provide a wide range of issues to solve. Unfortunately, the current scenario presents itself as one of fragmented development and dispersed investment, susceptible to legislative and social perception volatility. It is unclear what is the overall strategy and how the ongoing efforts are effectively contributing, piece-by-piece, towards its successful accomplishment. There is also a serious concern about the availability of human resources, materials, space, grid capacity, technologically optimized and demonstrated solutions, financial support, clear yet strict regulations, encompassing guidelines and recommendations, etc. To combat this, several mitigation measures were proposed, as summarized below

Mitigation measures

The European Green Deal provides a roadmap for the EU to achieve climate neutrality by 2050 through a series of policy initiatives, including the Just Transition Mechanism. This mechanism provides financial and technical support to regions facing significant challenges in transitioning to a low-carbon economy. It focuses on empowering individuals and communities by fostering employment, improving energy efficiency in housing, and addressing fuel poverty. Furthermore, it incentivizes businesses to engage in the green transition by offering investment opportunities, financial assistance, and innovation support, while also enabling regions to create green jobs, improve public transport systems, and invest in clean energy infrastructure.

Ports serve as pivotal hubs in this transition, bridging maritime and terrestrial systems and driving sustainable development in their hinterlands. They promote clean fuels and energy transition in maritime transport while contributing to the establishment of Net Zero Emission Port Terminals through renewable energy adoption and electrification. Ports also play a crucial role in building climate resilience, showcasing their importance in fostering sustainable development and aligning with the EU's broader objectives. Below is a summary of proposed mitigation measures to address hydrogen bottlenecks and support stakeholders, policymakers, and decision-makers in advancing these goals.

Concerning legislation, integrating the EU (2024) hydrogen and decarbonized gas laws into national frameworks will ensure uniform implementation across regions. Providing regulatory certainty on the role of non-renewable, low-carbon hydrogen is essential for fostering market adoption.

To address technical challenges, retrofitting kits and protocols for hydrogen-compatible machinery should be developed alongside incentives like fee discounts or taxes. Investing in R&D for cost-effective hydrogen-compatible equipment, supported by public and private funding, is essential. Pilot programs in ports can reduce adoption barriers by demonstrating hydrogen-powered equipment, while modular hydrogen production units and logistical networks can optimize space usage. Collaborations with nearby industrial zones for off-site hydrogen production and the use of digital twin technologies for port layout optimization are highly recommended. Ports should also prepare supply-chain strategies tailored to regional needs and leverage existing LNG infrastructure for gradual hydrogen integration.

On the economic front, introducing subsidies, tax breaks, or low-interest loans for early adopters in shipping and logistics is vital. International collaboration can pool resources for large-scale hydrogen projects, reducing costs. Cost-sharing agreements among ports, shipping companies, and governments will help distribute financial risks while scaling renewable energy production will make green hydrogen more competitive. Implementing carbon pricing mechanisms will further enhance hydrogen's economic appeal over fossil fuels.

These comprehensive measures, supported by strategic planning and multi-stakeholder collaboration, can address existing hydrogen bottlenecks and propel the transition to a sustainable, hydrogen-powered future.

References

[1] Anwar S, Li X. Production of hydrogen from fossil fuel: A review. Front Energy 2023;17:585–610. https://doi.org/10.1007/s11708-023-0886-4.
[2] Taveira-Pinto F, Iglesias G, Rosa-Santos P, Deng ZD. Preface to Special Topic: Marine Renewable Energy. Journal of Renewable and Sustainable Energy 2015;7:061601. https://doi.org/10.1063/1.4939086.
[3] OEE. Ocean Energy: Stats & Trends 2023. Brussels, Belgium: Ocean Energy Europe; 2024.
[4] WindEurope. Wind energy in Europe: 2023 Statistics and the outlook for 2024-2030. Brussels, Belgium: WindEurope; 2024.
[5] European Comission. Offshore renewable energy 2023. https://energy.ec.europa.eu/topics/renewable-energy/offshore-renewable-energy_en (accessed July 11, 2024).
[6] Brunik K, Thomas JJ, Clark CE, Duffy P, Kotarbinski M, Kee J, et al. Potential for large-scale deployment of offshore wind-to-hydrogen systems in the United States. J Phys: Conf Ser 2024;2767:062017. https://doi.org/10.1088/1742-6596/2767/6/062017.
[7] Allianz Commercial. A turning point for offshore wind. Allianz Commercial 2023. https://commercial.allianz.com/news-and-insights/news/offshore-wind-opportunities-risks-press.html (accessed July 11, 2024).
[8] Notteboom T, Haralambides H. Seaports as green hydrogen hubs: advances, opportunities and challenges in Europe. Marit Econ Logist 2023;25:1–27. https://doi.org/10.1057/s41278-023-00253-1.
[9] Ramakrishnan S, Delpisheh M, Convery C, Niblett D, Vinothkannan M, Mamlouk M. Offshore green hydrogen production from wind energy: Critical review and perspective. Renewable and Sustainable Energy Reviews 2024;195:114320. https://doi.org/10.1016/j.rser.2024.114320.
[10] Niblett D, Delpisheh M, Ramakrishnan S, Mamlouk M. Review of next generation hydrogen production from offshore wind using water electrolysis. Journal of Power Sources 2024;592:233904. https://doi.org/10.1016/j.jpowsour.2023.233904.
[11] WindPlus. Windfloat Atlantic | Offshore wind energy. Windfloat Atlantic 2020. https://www.windfloat-atlantic.com/ (accessed July 11, 2024).
[12] Pecher A, Kofoed JP, editors. Handbook of Ocean Wave Energy. vol. 7. Cham: Springer International Publishing; 2017. https://doi.org/10.1007/978-3-319-39889-1.
[13] Rusu E, Onea F. A review of the technologies for wave energy extraction. Clean Energy 2018;2:10–9. https://doi.org/10.1093/ce/zky003.
[14] Guo B, Ringwood JV. A review of wave energy technology from a research and commercial perspective. IET Renewable Power Generation 2021;n/a:26. https://doi.org/10.1049/rpg2.12302.
[15] Skopljak N. After first phase of operations, CorPower Ocean's wave energy device "proven at commercial scale." Offshore Energy 2024. https://www.offshore-energy.biz/after-first-phase-of-operations-corpower-oceans-wave-energy-device-proven-at-commercial-scale/ (accessed February 28, 2024).
[16] Ibarra-Berastegi G, Sáenz J, Ulazia A, Serras P, Esnaola G, Garcia-Soto C. Electricity production, capacity factor, and plant efficiency index at the Mutriku wave farm (2014–2016). Ocean Engineering 2018;147:20–9. https://doi.org/10.1016/j.oceaneng.2017.10.018.
[17] Rusu E, Guedes Soares C. Coastal impact induced by a Pelamis wave farm operating in the Portuguese nearshore. Renewable Energy 2013;58:34–49. https://doi.org/10.1016/J.RENENE.2013.03.001.
[18] Wello Oy. Technology – Wello Oy Penguin 2019. https://wello.eu/technology/ (accessed January 29, 2020).

[19] Directorate-General for Energy (European Commission), EDP NEW, FEM, Tecnalia, UCC, Dubranna J, et al. Study on the offshore energy potential in the Atlantic Ocean: final report. Publications Office of the European Union; 2023.

[20] EDF. Usine marémotrice de la Rance : produire une électricité décarbonée | EDF FR 2024. https://www.edf.fr/usine-maremotrice-rance/produire-de-lelectricite (accessed September 9, 2024).

[21] European Comission. EU strategy on energy system integration. Energy System Integration Will Make It Easier to Optimise and Modernise the EU's Energy System as a Whole 2020. https://energy.ec.europa.eu/topics/energy-systems-integration/eu-strategy-energy-system-integration_en (accessed October 4, 2024).

[22] De Nora. The evolution of traditional Alkaline Water Electrolysis 2024. https://energytransition.denora.com/en/content/news-the-evolution-of-traditional-alkaline-water-electrolysis.

[23] de Groot MT, Kraakman J, Garcia Barros RL. Optimal operating parameters for advanced alkaline water electrolysis. International Journal of Hydrogen Energy 2022;47:34773–83. https://doi.org/10.1016/j.ijhydene.2022.08.075.

[24] European Comission. Critical Raw Materials Act - European Commission 2023. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en (accessed October 4, 2024).

[25] Wolf SE, Winterhalder FE, Vibhu V, Haart LGJ (Bert) de, Guillon O, Eichel R-A, et al. Solid oxide electrolysis cells – current material development and industrial application. J Mater Chem A 2023;11:17977–8028. https://doi.org/10.1039/D3TA02161K.

[26] Vincent I, Bessarabov D. Low cost hydrogen production by anion exchange membrane electrolysis: A review. Renewable and Sustainable Energy Reviews 2018;81:1690–704. https://doi.org/10.1016/j.rser.2017.05.258.

[27] O.o.E.E.a.R. Hydrogen Production Related Links. EnergyGov 2024. https://www.energy.gov/eere/fuelcells/hydrogen-production-related-links (accessed October 4, 2024).

[28] Laval A. Water purification for green hydrogen production 2024. http://www.alfalaval.com/green-hydrogen-water-purification/ (accessed October 4, 2024).

[29] Axens. Purifying Low-Carbon Hydrogen: Techniques for Impurity Removal Across Applications 2020. https://blog.axens.net/purifying-low-carbon-hydrogen-techniques-impurity-removal-across-applications (accessed October 4, 2024).

[30] Azhari NJ, Erika D, Mardiana S, Ilmi T, Gunawan ML, Makertihartha IGBN, et al. Methanol synthesis from CO2: A mechanistic overview. Results in Engineering 2022;16:100711. https://doi.org/10.1016/j.rineng.2022.100711.

[31] IEA. New IEA study examines the future of the ammonia industry amid efforts to reach net zero emissions - News. Technology Roadmap Lays out Detailed Pathways towards More Sustainable Ammonia Production 2021. https://www.iea.org/news/new-iea-study-examines-the-future-of-the-ammonia-industry-amid-efforts-to-reach-net-zero-emissions (accessed October 4, 2024).

[32] Sage V, Patel J, Hazewinkel P, Yasin QUA, Wang F, Yang Y, et al. Recent progress and techno-economic analysis of liquid organic hydrogen carriers for Australian renewable energy export – A critical review. International Journal of Hydrogen Energy 2024;56:1419–34. https://doi.org/10.1016/j.ijhydene.2023.12.269.

[33] IEA. Global average levelised cost of hydrogen production by energy source and technology, 2019 and 2050 – Charts – Data & Statistics 2020. https://www.iea.org/data-and-statistics/charts/global-average-levelised-cost-of-hydrogen-production-by-energy-source-and-technology-2019-and-2050 (accessed October 4, 2024).

[34] Corbeau A-S, Merz A-K. Demystifying Electrolyzer Production Costs. Center on Global Energy Policy at Columbia University SIPA | CGEP 2023.

https://www.energypolicy.columbia.edu/demystifying-electrolyzer-production-costs/ (accessed October 4, 2024).
[35] Zhang Y, Jackson C, Krevor S. The feasibility of reaching gigatonne scale CO2 storage by mid-century 2024. https://doi.org/10.5281/ZENODO.11446272.
[36] Choi H, Lee H, Han J, Roh K. Revisiting the cost analysis of importing liquefied green hydrogen. International Journal of Hydrogen Energy 2024;82:817–27. https://doi.org/10.1016/j.ijhydene.2024.07.418.
[37] Mogensen MB, Chen M, Frandsen HL, Graves C, Hansen JB, Hansen KV, et al. Reversible solid-oxide cells for clean and sustainable energy. Clean Energy 2019;3:175–201. https://doi.org/10.1093/ce/zkz023.
[38] Govindan S. Green Ammonia – An Alternative Fuel. FutureBridge 2022. https://www.futurebridge.com/industry/perspectives-energy/green-ammonia-an-alternative-fuel/ (accessed October 4, 2024).
[39] Nytte S, Navrud S, Alfnes F. Social acceptance of new floating offshore wind power: Do attitudes towards existing offshore industries matter? Renewable Energy 2024;230:120855. https://doi.org/10.1016/j.renene.2024.120855.
[40] European Comission. Renewable hydrogen - European Commission 2024. https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/renewable-hydrogen_en (accessed September 25, 2024).
[41] European Comission. REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition. European Commission - European Commission 2022. https://ec.europa.eu/commission/presscorner/detail/e%20n/ip_22_3131 (accessed September 25, 2024).
[42] S&P Global. Electrolyzer manufacturing could become bottleneck in global hydrogen ramp-up 2022. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/electrolyzer-manufacturing-could-become-bottleneck-in-global-hydrogen-ramp-up-70893243 (accessed September 25, 2024).
[43] S&P Global. Green hydrogen tech-makers ready to unleash wave of European gigafactories 2022. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/green-hydrogen-tech-makers-ready-to-unleash-wave-of-european-gigafactories-71090933 (accessed September 25, 2024).
[44] Marsh P. Hydrogen electrolyser projects see 55 GW surge in 6 months | Envirotec 2024. https://envirotecmagazine.com/2024/04/30/hydrogen-electrolyser-projects-see-55-gw-surge-in-6-months/ (accessed September 25, 2024).
[45] Bernard MR. European Union Alternative Fuel Infrastructure Regulation (AFIR). Berlin, Germany: International Council on Clean Transportation (ICCT); 2023.
[46] Ludwig-Bölkow-Systemtechnik. Europe is increasingly adapting its growing hydrogen refuelling infrastructure to include heavy-duty vehicle refuelling. H2StationsOrg 2024. https://www.h2stations.org/press-release-2024-europe-is-increasingly-adapting-its-growing-hydrogen-refuelling-infrastructure-to-include-heavy-duty-vehicle-refuelling/ (accessed September 25, 2024).
[47] LNEG. OffShorePlan – Planeamento do Aproveitamento das Energias Renováveis OffShore em Portugal 2020. https://offshoreplan.lneg.pt/ (accessed August 23, 2023).
[48] DGRM. Plano de Afetação para Energias Renováveis Offshore (PAER). Ordenamento Do Mar Português 2023. https://www.psoem.pt/plano-de-afetacao-para-energias-renovaveis-offshore/ (accessed July 2, 2024).
[49] DGRM. Geoportal do Mar Português 2023. https://webgis.dgrm.mm.gov.pt/portal/apps/webappviewer/index.html?id=df8accb510bc4f3396 3d9b03bf3674b8 (accessed February 28, 2023).
[50] XXIII Portuguese Government. Preliminary proposal of specialized areas and seaports connected to the Nacional Electricity Grid and Transport. Portugal: Grupo de Trabalho para o planeamento e

operacionalização de centros electroprodutores baseados em fontes renováveis de origem ou localização oceânica; 2022.
[51] APA, Ministry of Environment and Energy of Portugal. Plano Nacional Energia e Clima 2030 (PNEC 2030). Lisboa, Portugal: Portuguese Environmental Agency (APA); 2024.
[52] Jesus J, Almodovar M, Simas T. Guia de licenciamento de projetos de energia renovável marinha em Portugal Continental. Centro de Energia Offshore, Lisboa, Portugal: WavEC; 2016.
[53] Government of Portugal. Resolução do Conselho de Ministros n.º 63/2020. vol. 1st Series. 2020.
[54] Government of Portugal. Decreto-Lei n.º 72/2022. vol. 1st Series. 2022.
[55] Government of Portugal. Decreto-Lei n.º 84/2022. vol. 1st Series. 2022.
[56] Government of Portugal. Portaria n.º 15/2023. vol. 1st Series. 2022.
[57] Directorate-General for Energy and Geology. Despacho n.º 30/2023. vol. 2nd Series. 2023.
[58] Government of Portugal. Portaria n.º 109/2024/1. vol. 1st Series. 2024.
[59] Government of Portugal. Portaria n.º 168/2024/1. vol. 1st Series. 2024.
[60] ERSE. Proposta de regulamentos do Sistema Nacional de Gás da responsabilidade da DGEG – Armazenamento Subterrâneo, Terminal de GNL e Rede de Transporte. 2021.
[61] Government of Portugal. Decreto-Lei n.º 22/2024. vol. 1st Series. 2024.
[62] BloombergNEF. Hydrogen Economy Outlook: Key messages. New York, USA: Bloomberg Finance L.P.; 2020.
[63] OMIP. Leilão eletrónico para a compra centralizada de biometano e hidrogénio 2024. https://www.omip.pt/pt/LGR2024 (accessed November 5, 2024).
[64] Government of France. Stratégie nationale pour le développement de l'hydrogène décarboné en France. Paris, France: Government of France; 2020.
[65] Government of France. Stratégie nationale portuaire. Paris, France: Government of France; 2021.
[66] France Hydrogène. Ecosystèmes portuaires et hydrogène : une ambition commune à bâtir. Paris, France: France Hydrogène; 2021.
[67] Ministerio de Agricultura, Alimentación y Medio Ambiente. Real Decreto 815/2013, de 18 de octubre, por el que se aprueba el Reglamento de emisiones industriales y de desarrollo de la Ley 16/2002, de 1 de julio, de prevención y control integrados de la contaminación. vol. BOE-A-2013-10949. 2013.
[68] UNECE. ADR 2023 - Agreement concerning the International Carriage of Dangerous Goods by Road. Geneva, Switzerland: United Nations; 2023.
[69] IRENA. Hydrogen purchase agreements (HPA). 15 - Hydrogen Purchase Agreements 2024. https://www.irena.org/Innovation-landscape-for-smart-electrification/Power-to-hydrogen/15-Hydrogen-purchase-agreements (accessed September 23, 2024).
[70] Ministerio para la Transición Ecológica y el Reto Demográfico. Políticas y legislación. Legislación europea relacionada con el hidrógeno 2024. https://www.miteco.gob.es/es/energia/hidrocarburos-nuevos-combustibles/hidrogeno/politicas-legislacion.html (accessed September 23, 2024).
[71] EirGrid, SONI. Annual Renewable Energy Constraint and Curtailment Report 2022. Ireland: EirGrid and SONI; 2023.
[72] Department of the Environment, Climate and Communications. Joint Declaration of Intent on cooperation in the field of green hydrogen between Ireland and Germany 2023. https://www.gov.ie/pdf/?file=https://assets.gov.ie/278826/72255664-5dc3-4dea-a615-6c5139251dff.pdf#page=null (accessed October 21, 2024).
[73] Department of the Environment, Climate and Communications. National Hydrogen Strategy 2023. https://www.gov.ie/en/publication/624ab-national-hydrogen-strategy/ (accessed October 21, 2024).
[74] Barry O'Halloran. Ireland could miss wind energy targets due to licensing delays. Waiting Times of Two Years for Foreshore Licences Will Hold Back Offshore Wind Projects 2021. https://www.irishtimes.com/business/markets/ireland-could-miss-wind-energy-targets-due-to-licensing-delays-1.4688122 (accessed October 21, 2024).

[75] Durakovic A. Irish Offshore Wind Project Delayed by Three Years as SSE Switches to New Consenting Regime. Offshore Wind 2022. https://www.offshorewind.biz/2022/03/24/irish-offshore-wind-project-delayed-by-three-years-as-sse-switches-to-new-consenting-regime/ (accessed October 21, 2024).
[76] GDG. National Port Study. Ireland: Gavin & Doherty Geosolutions; 2022.
[77] Duggan B, Carton JG. Ireland has no plausible plan to deliver offshore renewable energy. Irish Examiner 2024. https://www.irishexaminer.com/opinion/commentanalysis/arid-41472373.html (accessed October 21, 2024).
[78] BVG Associates, WEI. Building our Potential: Ireland's Offshore Wind Skills and Talent Needs. Ireland: BVG Associates and Wind Energy Ireland; 2024.
[79] Direção-Geral de Energia e Geologia. Energias Renováveis e Sustentabilidade 2019. https://www.dgeg.gov.pt/pt/areas-setoriais/energia/energias-renovaveis-e-sustentabilidade/ (accessed October 21, 2024).

CONTACT DETAILS

Victoria León Carpintero
Project Coordinator
EnergyLab
www.eu-hydea.eu