Interreg
Co-funded by the European Union
Italy – Croatia

BEYOND

INTERREG ITALY-CROATIA
PROGRAMME 2021 – 2027

BEYOND - Blue Economy sYnergies fOr sustainable Development

D.1.3.4 OWF technology and pilot regions infrastructure analasis

„BEYOND Policy and Infrastructure Analysis:

Fixed Offshore Systems for Wind, Hydrogen and Aquaculture".

INTERREG ITALY-CROATIA PROGRAMME 2021 – 2027
Standard Call for Proposals
Programme priority: Sustainable growth in the blue economy

Specific objective: 1.1: Developing and enhancing research and innovation capacities and the uptake of advanced technologies

Project: **BEYOND - Blue Economy sYnergies fOr sustainable Development**

Work Package:	1 - Adriatic blue economy sectors in business as usual surrounding
Activity:	1.3.4 OWF technology and pilot regions infrastructure analysis
WP coordinator:	PP5 OGS
Deliverable:	D.1.3.4 OWF technology and pilot regions infrastructure analysis

Version:	FINAL	**Date:**	08/2025
Type:	Report		
Availability:	PUBLIC		
Responsible Partner:	PP5 County of Split and Dalmatia		
Involved Partner	PP1 IRENA, PP2 OGS, PP3 RITEH, PP4 Regione Puglia, PP5 SDC, PP6 T2i, PP8 MRRFEU		
Editor:	PP5 County of Split and Dalmatia		
Contributors:	All PPs		

Project website: https://www.italy-croatia.eu/web/beyond

Institution responsible for technical preparation of the study (external consultant):

Adria Innovation Harbour

info@aih.hr

VAT HR39854822974|PIC 886928619

Authors:

Assistant Professor, PhD Hrvoje Mikulčić, mag.ing.mech.

PhD Mislav Šagovac, MSc in oec.

PhD Vlatka Vaniček, MSc in geol.

Ana Glavina, mag. oecol.

Assistant Professor, PhD Jakov Baleta, mag.ing.

Associate Professor, PhD Luka Perković, MSc in Mechanical Engineering

Preparation for the purpose of: Preparation of document 1.3.4. OWF technology and pilot regions infrastructure analysis for the purposes of implementing the Blue Economy sYnergies fOr sustainable Development (BEYOND) project, Interreg VI-A, Italy- Croatia ITHR0200543

Disclaimer:

This document reflects the views of the author(s) and is intended solely for informational and analytical purposes within the context of hydrogen and offshore renewable energy development. The interpretations, assessments, and conclusions presented herein do not necessarily represent the official positions or policies of any national authority, regional administration, project consortium, or funding institution. Neither the authors nor any associated organizations shall be held responsible for the use that may be made of the information contained in this document.

Contents

1. Introduction & Executive Summary

From the very beginning of the European Green Deal, hydrogen has been regarded as a central solution. It therefore came as no surprise when the President of the European Commission, Ursula von der Leyen, stated that clean hydrogen could be considered a fuel for "heavy industry, capable of powering our cars, trucks, and airplanes, storing energy seasonally, heating our homes… – all with nearly zero emissions." Relatively soon after the adoption of the Green Deal, Europe introduced its Hydrogen Strategy in 2020, followed by Croatia only two years later, while Italy did the same at the end of 2024. To ensure that progress did not stop with the adoption of strategies, the International Energy Agency (IEA) also welcomed the growing interest in clean hydrogen in recent years, noting that if all hydrogen-related projects currently under development were to be realized, by 2030 low-emission hydrogen production could reach 16–24 Mt annually (9–14 Mt from electrolysis and 7–10 Mt from fossil fuels with CCUS). Furthermore, according to the IEA (https://www.iea.org/reports/global-hydrogen-review-2022/executive-summary), despite the projected growth, meeting the climate commitments of EU Member States would require 34 Mt of low-emission hydrogen production annually by 2030. A pathway compatible with achieving net-zero emissions globally by 2050 would demand an even higher figure – approximately 100 Mt.

At the same time, the process of water electrolysis for hydrogen production still relies on relatively expensive technology, and the required amount of electricity is significant, ranging between 4.5–5.5 kWh per m^3 (Gao, X. et al., 2024).

Therefore, to achieve these ambitious plans, it is essential to secure sufficient energy for hydrogen production, adequate space, and the necessary technical, technological, and administrative conditions for the process of water molecule separation and hydrogen generation. This applies particularly to the production of green hydrogen at sea, since only hydrogen produced in this way can serve as a key link between renewable energy sources and the decarbonisation of economic activities. Indeed, such green hydrogen, obtained through the electrolysis of water using renewable electricity, represents one of the most important solutions for reducing emissions in hard-to-abate sectors such as industry and transport.

Building on the growing importance of offshore renewable energy in achieving the European Union's climate neutrality goals, this document explores alternative ways of utilizing energy generated by offshore wind farms, focusing not only on electricity transmission to the mainland, but also on its direct conversion into green hydrogen. Offshore hydrogen production, carried out alongside electricity generation, represents an optimal solution for maximizing the use of renewable energy. The produced hydrogen can be stored or used on-site, particularly during periods when electricity generation exceeds grid capacity or demand, ensuring a stable and flexible energy system.

To support the development of integrated offshore energy systems, this study emphasizes the importance of spatial planning, the condition and availability of existing infrastructure, and technological solutions for hydrogen production, storage, and transport. Special attention is given to pilot regions in the Adriatic, where offshore wind farms can serve as reliable energy sources for electrolysis and hydrogen generation.

The analysis assesses the potential for integrating offshore wind energy and green hydrogen production in Italy and Croatia, examining technological, infrastructural, and spatial aspects in line with European strategic objectives. Within the framework of the European Green Deal, the *Fit for 55*, and the EU Regulation on the Internal Markets for Renewable and Natural Gases and Hydrogen (EU 2024/1789), both countries recognize hydrogen as a key energy carrier for the decarbonization of industry, transport, and the energy sector.

Italy has already developed a strong regulatory and infrastructural foundation and is advancing the Italian Hydrogen Backbone, a national hydrogen transport network projected to reach approximately 2,300 kilometers by 2030. Croatia, through its national operators Plinacro and HOPS, is entering the initial phase of planning and developing its future hydrogen network within the *European Hydrogen Backbone* initiative.

The study identifies the Veneto and Puglia regions in Italy and the Istria and Split-Dalmatia counties in Croatia as the most promising areas for developing integrated offshore renewable energy systems. These regions combine favourable natural conditions, such as wind potential, shallow seas, and proximity to major ports, with developed electricity and gas infrastructure and a relatively low share of protected. Nevertheless, several challenges remain, including environmental constraints, regulatory complexity, and the need for enhanced technical capacity.

Through coordinated actions and cross-border cooperation, particularly within INTERREG and similar EU programmes, Italy and Croatia have the potential to position the Adriatic Sea as a regional hub for clean energy and innovation. Such an approach would not only contribute to the European energy transition but also strengthen regional resilience, competitiveness, and long-term sustainability across the Adriatic basin.

2. Methodology

In the course of the work, analysis and synthesis of secondary sources, i.e. desk research, was applied. Since the purpose of the project is to assess potential and develop recommendations, no primary research was conducted; instead, existing studies, strategic documents, and relevant reports were used.

The research and the process of drafting the document included the following steps:

- Collection of available data, i.e. review of relevant national and European strategic documents, legislation, statistical databases, and expert reports related to the project's topic.
- Selection of data relevant to the project objectives, considering timeliness, reliability, and alignment with specific research questions.
- Systematisation of the selected data and linking it to the project objectives.
- Preparation of a report in the form of a structured overview, providing a solid basis for the development of further deliverables, conclusions, and recommendations.

3. Findings and Analysis

This chapter provides an overview of key findings and an analysis of the regulatory, technical, and infrastructural framework relevant to the development of offshore wind farms (OWF), hydrogen technologies, and the blue economy sector in Croatia and Italy. Special attention is devoted to the legislative frameworks of the two countries, as these represent the fundamental prerequisites for planning, implementation, and future integration of renewable energy sources and hydrogen solutions into national and regional systems.

Beyond regulatory aspects, the technical context for offshore wind farms and blue economy installations is also analysed, including requirements and constraints related to infrastructure and environmental conditions. Additionally, the chapter addresses the status and challenges related to critical infrastructure in the pilot regions, as well as the availability and capacities of technology and service providers.

The aim of this chapter is to provide a comprehensive basis for understanding the existing environment, to identify opportunities and barriers to development, and to highlight relevant stakeholders and resources that can support the implementation of projects in the fields of renewable energy, hydrogen, and the blue economy.

3.1. Legislation for OWF and Blue Economy Sectors with Fixed Offshore Installations in EU

For the implementation of large and strategically important projects in the field of hydrogen, the existence of a comprehensive regulatory framework is essential, enabling the execution of all processes – from research and development to production and application. Hydrogen has been recognised as one of the key elements for achieving climate neutrality, a significance further reinforced in July 2020 when the European Union adopted the Hydrogen Strategy for a Climate-Neutral Europe (European Commission, 2020). In this document, green hydrogen produced from renewable sources is clearly defined to enable the deep decarbonisation of the European economy by 2050. This is emphasised in the context of the fact that most of the hydrogen in the EU is still produced from fossil fuels, primarily natural gas.

A key document through which the European Commission established hydrogen as a fundamental energy carrier for achieving climate neutrality by 2050 is the *European Hydrogen Strategy* 2020/2242(INI). At the core of this strategy lies green hydrogen, produced by water electrolysis using renewable sources such as wind and solar, without greenhouse gas emissions. It is precisely this form of hydrogen that has been recognised as the decisive factor in achieving climate neutrality (European Commission, 2020)

The Strategy itself foresees the development of the hydrogen economy in three stages. In the first stage, from 2020 to 2024, the objective is to install at least 6 GW of electrolyser capacity and produce up to 1 million tonnes of renewable hydrogen annually. According to the projections, hydrogen will initially be used primarily for the decarbonisation of energy-intensive industries such as steel, cement, and chemical production, as well as in heavy road transport. The second stage, covering the period from 2025 to 2030, anticipates a significant expansion of capacity to 40 GW and the production of up to 10 million tonnes. In the final stage, after 2030, hydrogen is expected to become an integral part of all sectors of the economy – industry, transport, energy, and heating – while also enabling the stabilisation of electricity grids, thus making it a key element of a secure and flexible energy system.

Special attention in the Strategy is also devoted to the creation of a hydrogen market and the establishment of a regulatory framework. The Strategy foresees the introduction of a certification system and guarantees of origin, as well as the development of infrastructure including pipelines, storage facilities, refuelling stations, and ports (European Commission, 2020).

Based on the above-mentioned Strategy, the creation of a regulatory and legislative framework began to gradually shape a favourable environment – both legal and market-related – for the production, distribution, and use of green hydrogen. A key role in this process is played by the updated Renewable Energy Directives, RED II and RED III (Directive (EU) 2018/2001 and Directive (EU) 2023/2413). These directives set new targets for the transport and industry sectors and introduced a special category of fuels – the so-called *Renewable Fuels of Non-Biological Origin* (RFNBO), i.e. gaseous and liquid fuels produced from non-biomass sources, including green hydrogen obtained by electrolysis of water using renewable energy. With the newly established consumption, and consequently production targets, green hydrogen has been clearly positioned as one of the key solutions for the decarbonisation of sectors with particularly high emissions (European Commission, 2018; European Commission, 2023).

As noted, the Directive does not remain on the level of concepts but also sets concrete targets. In the transport sector, it is foreseen that by 2030 at least 1% of total energy consumption will come from RFNBO fuels, while in industry the share of renewable hydrogen must reach at least 42% by 2030 and 60% by 2035. These targets represent a significant step forward, as they both require and enable a rapid adaptation of the industry and energy sector, as well as an accelerated development of technologies for the production and application of renewable hydrogen.

In addition to the Strategy and the Renewable Energy Directives, activities related to offshore green hydrogen production are also supported by Directive 2014/89/EU *on Maritime Spatial Planning*. Although the Directive does not explicitly mention the production of green hydrogen, it strongly promotes activities based on the blue economy.

This indicates that installations for renewable energy production will be encouraged and supported, but only with the prior allocation of space and safeguarding measures for other maritime stakeholders. In other words, the Directive requires planning with an ecosystem-based approach, whereby the different functions of both the sea and the coast must be considered (European Parliament and Council, 2014).

For the practical implementation of the above-mentioned strategies and directives, it was necessary to adopt various delegated acts, among which a special place is held by Regulation (EU) 2023/1184. This Regulation sets out precise criteria under which hydrogen produced by electrolysis can be counted as renewable. One of the criteria for classifying hydrogen as an RFNBO fuel is, for example, the origin of the electricity required for electrolysis. To comply with the rules, this electricity must either be supplied directly from renewable sources or via the grid, in which case it must be recognised as 100% renewable. Furthermore, hydrogen that qualifies as renewable must be linked to renewable energy installations that are either new or additional, while the electrolyser and the associated facility must be located within the same or a connected zone. In other words, for hydrogen to meet the conditions and be certified as an RFNBO fuel, both spatial and temporal components must be defined. The Regulation also prescribes conditions for issuing and collecting documentation, certification, and reporting. In this way, it lays the foundations for a transparent and sustainable development of the hydrogen market in the EU, particularly for applications in transport and industry. It is precisely this type of green hydrogen – linked to integrated offshore wind farm and electrolyser installations – that forms the subject of this project, fully aligned with the objectives and strategy of the European Commission (European Parliament and Council, 2023a)

A further strong boost to hydrogen networks has been provided by the revised TEN-E 2022/869 (EU) Regulation, which sets out and mandates the interconnection of Member States' energy infrastructures and the inclusion of a number of priority corridors and areas into an integrated framework.

In addition, it should be emphasised that one of the main objectives of the Regulation is investment in hydrogen and carbon dioxide networks, as well as the introduction of offshore/marine grids. Moreover, the Regulation has rightly identified the excessively long administrative procedures and prescribes the acceleration of permitting processes, while also proposing the establishment of a single point of contact per project in each Member State (European Parliament and Council, 2022).

The legislative framework has been further strengthened by the adoption of Directive (EU) 2024/1788 (the Hydrogen and Gas Market Directive) and Regulation (EU) 2024/1789 on renewable and natural gases and hydrogen, which, together with the revised TEN-E Regulation of 2022, form a new regulatory system for the construction, access, and repurposing of networks intended for natural gas in the EU. These provisions define in detail what constitutes the hydrogen system (infrastructure, networks, storage facilities, and terminals) and regulate the rules for market functioning and for repurposing existing natural gas infrastructure for the transport of pure hydrogen. For countries such as Croatia and Italy, which have a well-developed gas network, this possibility represents a significant advantage as it enables a faster and cheaper transition compared to the scenario of building entirely new networks. In addition, the hydrogen network itself is defined (a network of onshore and offshore pipelines used to transport high-purity hydrogen for delivery to customers), along with a regulated description of access to hydrogen networks (transport and distribution), which is based on published tariffs. A particularly important element of *Regulation (EU) 2024/1789* is the establishment of the European Network of Network Operators for

Hydrogen (ENNOH). This network will consist of certified hydrogen transmission system operators from the Member States, with the purpose of fostering the development and functioning of the internal hydrogen market, facilitating cross-border trade, and ensuring efficient and coordinated management of the European hydrogen transport network – thereby supporting the sustainable development of the hydrogen market across the Union (European Parliament and Council, 2024a; European Parliament and Council, 2024b).

The final step in establishing the European Union's regulatory framework for hydrogen, which already includes rules for renewable hydrogen and renewable fuels of non-biological origin (RFNBO), is linked to the adoption of a forthcoming delegated act, building on the Hydrogen and Gas Market Directive (*Directive (EU) 2024/1788*). This act will establish the methodology for calculating greenhouse gas emissions for low-carbon hydrogen and fuels. With it, the introduction of clear criteria will be completed, ensuring transparency and predictability of investments, thereby encouraging faster and more secure development of clean hydrogen production capacities in Europe. The methodology will apply equally to fuels produced within the EU and to imports, including those derived from natural gas with the application of CCS technologies.

The delegated act still needs to undergo the parliamentary procedure, and once this process is completed, the methodology will become a key tool for the development and certification of low-carbon fuels in the European Union (European Union, forthcoming).

There are also secondary legislative acts related to consumption, and thus to the development of green hydrogen. One example is the *ReFuelEU Aviation Regulation*, adopted in 2023 (Regulation (EU) 2023/2405), with the aim of reducing emissions in aviation and promoting the use of Sustainable Aviation Fuels (SAF). The Regulation obliges all airports in the European Union, as of 2025, to ensure a minimum share of sustainable fuels in aircraft supply, starting at 2%, gradually increasing to 6% by 2030, and reaching 70% by 2050. For this project, the provision on synthetic fuels, such as e-kerosene, produced using green hydrogen, is of particular importance. Another key act is the *FuelEU Maritime Regulation* (Regulation (EU) 2023/1805), also part of the "Fit for 55" package, which focuses on reducing emissions in the maritime sector. It introduces the obligation of gradually reducing the greenhouse gas (GHG) emission intensity of the energy used by ships, starting at 2% by 2025 and reaching 80% by 2050, compared to the reference level from 2020. The rules apply to all ships above 5,000 GT calling at EU ports, regardless of their flag or country of origin (European Parliament and Council, 2023d; European Parliament and Council, 2023c).

The role of hydrogen in maritime transport is not limited to powering ships via fuel cells; more importantly, it is reflected in supporting the production of new types of fuels that can replace heavy marine fuels. Accordingly, the Regulation aims at developing not only hydrogen itself but also its derivatives – e-ammonia, e-methanol, and other synthetic fuels produced from green hydrogen. These fuels have the potential to ensure full decarbonisation of maritime transport, particularly for larger cargo vessels and international shipping routes. The Regulation also foresees the mandatory use of onshore electricity supply in major ports from 2030 onwards, which further reduces emissions during ships' stays in port. In this way, *FuelEU Maritime* contributes to establishing a regulatory framework that fosters the development of infrastructure and investments required for the wider application of hydrogen-based solutions in maritime transport (European Parliament and Council, 2023c). In addition to the described needs of maritime and air transport, the regulation that mandates easier deployment and use of hydrogen in road transport is Regulation (EU) 2023/1804 (AFIR). It obliges Member States to build a minimum infrastructure for alternative fuels, including hydrogen refuelling stations every 200 km along the main transport corridors by 2027, suitable for both passenger vehicles and heavy-duty trucks. By 2030, hydrogen infrastructure is expected to be in place across the entire network and in major urban areas. These provisions create the necessary preconditions for the development of the hydrogen vehicle and transport market in the EU, which would otherwise remain unusable without such planned infrastructure. At the same time, this is the first document that sets binding targets for the hydrogen refuelling network. In maritime transport, the Regulation also establishes the obligation to deploy onshore electricity supply infrastructure in the main seaports by 2030, thus enabling emission reductions while ships are at berth. Similarly, obligations are prescribed for aviation in the form of onshore power supply for airports (e.g., for parked aircraft) (European Parliament and Council, 2023b).

Through the above-mentioned documents, the European Union has established a comprehensive and stable regulatory framework covering all key elements: the production and certification of green hydrogen, sectoral targets in industry and transport, and the construction and management of infrastructure. Such a framework creates clear conditions for the faster development of projects, pilot initiatives, and innovative solutions, thereby enabling the achievement of climate neutrality by 2050. For EU Member States such as Croatia and Italy, this robust legislative framework opens numerous opportunities. Both countries possess significant renewable energy potential – particularly along the coastline – as well as developed ports, industrial hubs, and gas networks. Support for local initiatives and integration with the European TEN-E infrastructure further strengthens the possibility of using hydrogen as a strategic energy and industrial lever in the transition towards a climate-neutral economy.

3.2. Legislative Framework for the Development of Hydrogen Technologies in Croatia

One of the first documents to mention hydrogen is the Integrated National Energy and Climate Plan of the Republic of Croatia for the period 2021–2030. This document sets Croatia's 2030 targets in terms of emission reduction, increased shares of renewable energy, energy efficiency, and related objectives. It was adopted in 2019 and already at that time referred to the use of hydrogen as a fuel. It outlined the details of incentives for such alternative fuels, including subsidies for vehicles and vessels powered by hydrogen, as well as support for infrastructure. The Plan also anticipated that after 2030, the increasing share of hydrogen in the energy mix would become an integral part of Croatia's decarbonisation strategy (Government of the Republic of Croatia, 2025).

The Energy Development Strategy of the Republic of Croatia until 2030 with an outlook to 2050 (Official Gazette 25/2020) sets out the vision for Croatia to become a low greenhouse gas emission country, with a significant share of renewable energy in the energy mix by 2030 and a stronger integration of clean technologies by 2050. The analysis within the Strategy presents the number of electrolysers and the capacity required under different scenarios to produce green hydrogen (RFNBO). The document emphasises the increase in the share of renewable energy sources, particularly solar, wind, and hydropower, alongside strengthened energy efficiency across all sectors. It foresees the modernisation and expansion of the electricity grid to enable the integration of large amounts of renewable energy. In the transport and industry sectors, the Strategy highlights the need for the gradual introduction of alternative fuels, specifically noting the role of hydrogen in decarbonising high-emission sectors

(Government of the Republic of Croatia, 2020). The Strategy also highlights the possibility of using the existing gas infrastructure for blending hydrogen with natural gas as a transitional solution. Although hydrogen is not elaborated in detail in the main text, its strategic importance in the medium and long term is recognised. In the field of research and development, the Strategy foresees the promotion of innovations related to technologies for the production and application of green hydrogen. The document also stresses the importance of alignment with European policies and climate neutrality objectives, including RED II and REPowerEU. Key challenges for implementation remain administrative barriers, financial sustainability, and the need for faster infrastructure development. In this way, the Strategy establishes the foundations for the integration of hydrogen into Croatia's energy system, although more detailed plans are left to subsequent implementing documents.

In order to direct development towards economic growth with reduced energy consumption and greater use of renewable sources, the Low-Carbon Development Strategy of the Republic of Croatia until 2030 with an outlook to 2050 (Official Gazette 63/2021) was adopted. The Strategy assumes that the number of vehicles powered by hydrogen will grow after 2030, and under some scenarios it is expected that hydrogen vehicles could make up around 1–2% of the total vehicle fleet by 2050.

According to the National Recovery and Resilience Plan 2021–2026 (adopted in 2021), Croatia plans to connect 1,500 MW of new renewable energy sources to the energy system by the end of 2024, with a total of around 2,500 MW of installed capacity foreseen by 2030. The goal is to ensure the production of clean energy sufficient to meet domestic needs (Government of the Republic of Croatia, 2021a; Government of the Republic of Croatia, 2021b).

Another document adopted in 2021 is the Scenario for Achieving Climate Neutrality in the Republic of Croatia by 2050, which contains numerous references to hydrogen, increasingly recognised as a strategic component for achieving the set targets. It was developed with the goal for Croatia to reach climate neutrality by 2050, meaning that greenhouse gas emissions are reduced to net zero, with the remaining emissions removed through CO_2 sinks and other measures. The document covers analyses for both the energy and non-energy sectors, assuming a strong reduction in the use of fossil fuels, to be replaced by renewable energy sources, electricity, and alternative fuels – including hydrogen and synthetic fuels. Natural gas is expected to be almost completely phased out of consumption by 2050, with possibilities for blending with hydrogen and for using the network for the transport and storage of biomethane and hydrogen. Furthermore, in the transport sector a significant reduction in oil and derivatives consumption is anticipated, alongside an increase in the use of electric vehicles as well as vehicles running on alternative fuels, including hydrogen (EKONERG, 2021). In industry, the development and application of technologies for high-temperature processes are foreseen, which must shift from fossil fuels to hydrogen or other clean sources. The document also includes assessments of economic and social impacts, covering costs and benefits, as well as plans for a socially and regionally just transition. From the perspective of hydrogen, the scenario identifies it as one of the key elements in medium- and long-term changes: hydrogen production, its integration into transport and industry, and its role in energy transmission and storage.

Following the strategic direction of the European Union, in 2022 Croatia adopted its own Croatian Hydrogen Strategy until 2050 (Official Gazette 40/2022). This document establishes the national framework for the development of hydrogen production and use, with a focus on renewable and low-carbon hydrogen as a substitute for conventional fossil fuels. It defines national goals, priorities, and measures for the development of hydrogen production, distribution, and application. The Strategy emphasises that a hydrogen-based economy can play a key role in the energy transition, particularly in sectors where electrification is not possible or cost-effective (Government of the Republic of Croatia, 2022).

The Croatian Hydrogen Strategy also provides a detailed framework to produce hydrogen and synthetic fuels in line with the principles of the RED III Directive, under which Croatia must achieve at least 1% renewable hydrogen in road transport, 1.2% in maritime transport, more than 0.7% hydrogen-based synthetic fuels in aviation, and 42% green hydrogen in existing industrial hydrogen consumption. Current hydrogen production – and therefore consumption – amounts to around 70,000 tonnes (data for 2021, energy sector) and is entirely based on hydrogen produced from fossil fuels, i.e. natural gas (Government of the Republic of Croatia, 2022).

Within the development plan, the main guidelines for Croatia's strategic positioning within the European hydrogen market are defined – from production and storage to transport, distribution, and end-use. Special emphasis is placed on the involvement of key stakeholders, ranging from public authorities and scientific institutions to industry and civil society. Ultimately, the objective of the Republic of Croatia is also the development of hydrogen infrastructure, leveraging its strategic position in Europe. This includes the establishment of hydrogen production facilities, storage and refuelling systems, particularly along the Trans-European Transport Network (TEN-T). The development of this infrastructure is designed to support both domestic needs and the potential for hydrogen export.

Within the development plan, the main guidelines for Croatia's strategic positioning within the European hydrogen market are defined, from production and storage to transport, distribution, and end-use. Special emphasis is placed on the involvement of key stakeholders, ranging from public authorities and scientific institutions to industry and civil society. Ultimately, the objective of the Republic of Croatia is also the development of hydrogen infrastructure, leveraging its strategic position in Europe. This includes the establishment of hydrogen production facilities, storage and refuelling systems, particularly along the Trans-European Transport Network (TEN-T). The development of this infrastructure is designed to support both domestic needs and the potential for hydrogen export.

The Strategy also defines the role and models of cooperation among key stakeholders, like state authorities, institutions, research entities, professional associations, non-governmental organisations, financial institutions, public enterprises, and promoters of hydrogen projects, establishing clear guidelines and a timeline for implementation. Based on the status of hydrogen projects in the Republic of Croatia, as well as the institutional and regulatory framework, priority activities up to 2030 are proposed in the form of pilot projects.

From a legislative perspective, the Strategy is based on the Act on the System of Strategic Planning and Development Management of the Republic of Croatia, the Energy Act, and the Gas Market Act. It is also aligned with national documents such as the Energy Development Strategy of the Republic of Croatia until 2030 with an outlook to 2050 (Official Gazette 25/2020), the National Energy and Climate Plan (NECP), and the Low-Carbon Development Strategy of the Republic of Croatia until 2030 with an outlook to 2050 (Official Gazette 63/2021). Furthermore, other laws in Croatia regulate the possibilities for hydrogen use, such as the Act on Amendments to the Biofuels for Transport Act (Official Gazette 52/2021), which envisages the introduction of hydrogen to the

Croatian market, and the Act on the Deployment of Alternative Fuels Infrastructure (Official Gazette 120/2016), which defines technical specifications for hydrogen refuelling stations.

The Strategy is built on four pillars that define the main guidelines for developing a hydrogen-based economy: hydrogen production; hydrogen storage and transport; hydrogen use; and education, research, and innovation. In line with both EU policy and the Strategy, the decarbonisation of the energy sector is moving towards the installation of new renewable energy capacities, which can also be used for hydrogen production. Part of the generated energy is directed to end-users in the form of electricity through the Croatian power system, while another part may be used to produce renewable hydrogen directly at the site of electricity generation. In addition to *in situ* green hydrogen production, a portion of the generated electricity may also be transmitted to other renewable hydrogen production sites, e.g. onshore, if it is not more expensive than electricity produced at the site of renewable hydrogen generation. Beyond production, the Strategy also outlines methods of hydrogen storage and transport, aimed at meeting the needs of transport, industry, buildings, and other sectors. Hydrogen storage can be carried out in gaseous form and, later, in liquid form – the latter being viable only for certain specialised applications where compressed hydrogen cannot meet volume requirements. Hydrogen transport may be carried out using trailers with tanks for hydrogen in gaseous or liquid state, employing road, rail, maritime, and inland waterway transport. It can also be transported through pipelines (hydrogen pipelines) from the place of production to the place of consumption. Another option is a gas transport system in which hydrogen is blended with natural gas within the transmission system, followed by subsequent separation of hydrogen from the mixture if pure hydrogen is required at a given location. However, if only energy is needed, separation is not required.

Considering the developed gas network as well as existing pipelines that are currently out of operation, in the long term, and depending on consumption trends, it is possible to use these pipelines for hydrogen transport. The Strategy also clearly states that it is possible to develop offshore wind farm projects to produce renewable electricity and renewable hydrogen, which could then be transported via the existing gas pipeline infrastructure to meet the needs of both Croatia and Italy.

The Republic of Croatia has a well-developed gas transmission and distribution system. The total length of the gas transmission system exceeds 2,500 km, while the distribution system extends over 18,000 km, directly supplying more than 680,000 end-users across 19 of the 20 counties and the City of Zagreb (Government of the Republic of Croatia, 2022). The gas transmission system is interconnected with the regional and European gas network through interconnections with Hungary and Slovenia, and, via the liquefied natural gas (LNG) terminal and evacuation pipelines, it is also connected to the global market. This enables the transport of gas to both regional and European markets.

In the first phase of developing green hydrogen production and consumption, infrastructure needs for transport will be relatively small, as production is planned close to or directly at the point of consumption. In later stages, however, hydrogen infrastructure will serve not only for the transport of hydrogen for industrial and transport applications but also for balancing electricity generation and demand and providing heat for residential and commercial buildings.

Ultimately, active participation is also foreseen in the development of the future pan-European hydrogen transport network (*Backbone Transmission Infrastructure*).

The first projects identified for the use of green hydrogen are those in the transport sector, which also implies ensuring adequate infrastructure for the smooth operation of such vehicles throughout the entire territory of Croatia. The next step is the application of hydrogen in industry, where it is crucial to secure the production of sufficient amounts of renewable hydrogen to serve as feedstock in industrial processes. This requires the establishment of adequate electrolyser capacity, as well as the necessary upgrading and modernisation of the electricity grid and the gas transmission system.

The Strategy outlines two possible development scenarios: the first scenario is linked to climate neutrality (S1), while the second is based on the assumptions of accelerated growth of a hydrogen-based economy (S2). For each scenario, projections are provided regarding hydrogen production, electrolyser capacity, macroeconomic impacts, capital investments in hydrogen production infrastructure, GDP growth, and employment. Figure 1 presents a graph showing the projected growth of hydrogen production and the development of electrolyser capacity under both scenarios (Figure 1)

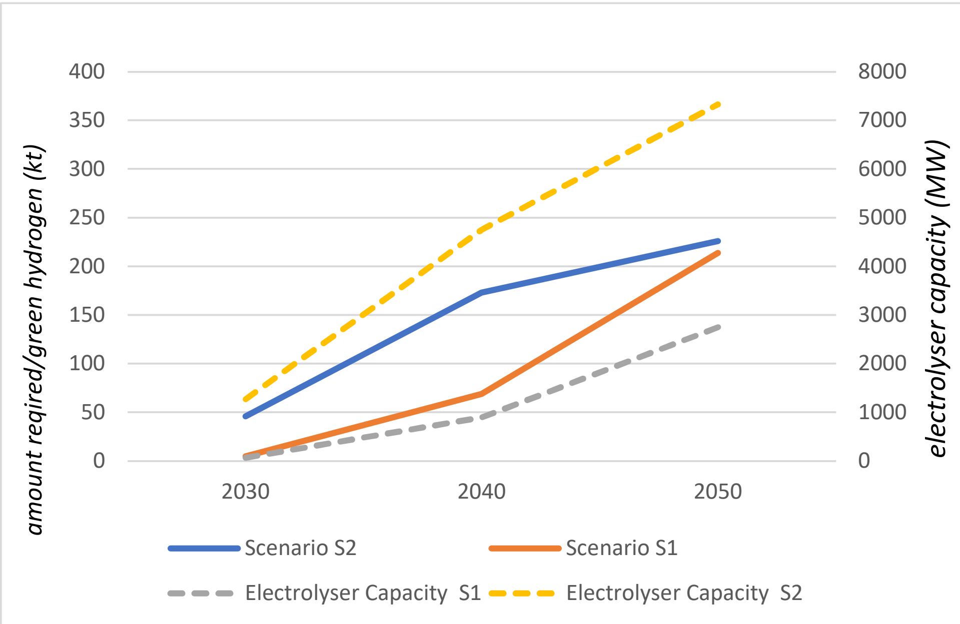

Figure 1 Projected growth of hydrogen production and electrolyser capacity for two scenarios

In addition to the above-mentioned documents, the year 2025 continued the adoption of regulations related to green hydrogen, including the Critical Infrastructure Act (Official Gazette 89/2025). This Act establishes the legal framework for the identification, protection, and management of key systems whose disruption could have significant consequences for security, health, the economy, and social stability in the Republic of Croatia.

In this context, hydrogen has been recognised as part of the sector encompassing production, storage, and transmission operators, thereby clearly confirming its strategic importance in the energy transition and in the security aspects of the new energy infrastructure.

The inclusion of hydrogen in this Act makes it possible to establish high safety standards for its production, storage, and transport, while also providing access to protection and financing mechanisms related to critical systems. In this way, the Act becomes an important tool for ensuring the reliability and resilience of hydrogen value chains, particularly in the context of cross-border initiatives such as those between Croatia and Italy.

All the above-mentioned documents describe pathways for transformation towards a low greenhouse gas emission society through potential investments in green business models, technologies, innovation, and development.

In the Maritime Code of the Republic of Croatia (Official Gazette 181/04, 76/07, 146/08, 61/11, 56/13, 26/15, 17/19), the term hydrogen, its production, transport, or related activities, is not directly mentioned, as the document is primarily focused on the maritime and submarine areas of the Republic of Croatia and on the legal relations therein, on navigation safety in the internal waters and territorial sea of the Republic of Croatia, on the protection and preservation of natural marine resources and the marine environment, on relations concerning vessels, on general navigation safety, on the application of maritime law; and on the protection of the marine environment and vessels. None of the provisions or definitions contained in the Code specifically cover the infrastructure required for the production, transport, storage, or use of hydrogen as a distinct category. However, Article 5 of the Maritime Code defines *fixed offshore installations*, i.e. a maritime installation entirely or partly embedded in the seabed or laid on the seabed, not intended for navigation, as well as floating installations permanently moored or anchored at sea, also not intended for navigation. This category includes infrastructural elements such as wind farms, green hydrogen production facilities, and pipelines. Furthermore, Article 33 stipulates that the Republic of Croatia exercises sovereign rights in its exclusive economic zone for the purpose of producing energy from the sea, marine currents, and wind. In conclusion, as with wind farms, the installation of facilities required for the production and transport of green hydrogen will also need to follow the provisions of the Maritime Code in the process of obtaining approvals and permits for the exploration and installation of infrastructural elements – particularly in relation to navigation safety and the protection of the marine environment.

In line with Directive 2014/89/EU establishing a framework for maritime spatial planning (MSP Directive), which obliges all Member States to develop plans for the sustainable management of their marine areas, Croatia has initiated the process of adopting spatial plans for its marine areas. This is carried out within the framework of national legislation governing the use of land and sea space, with an emphasis on sustainable development, environmental protection, and the alignment of different sectoral interests. For Croatia, given its long coastline and the importance of the Adriatic Sea, the integration of MSP into the spatial planning system represents an important step towards aligning national development goals with European policies and international obligations. The harmonisation of national legislation with the MSP Directive is particularly significant in the context of the Adriatic Sea, which Croatia shares with Italy and other neighbouring states. While Italy has already adopted its national maritime spatial plan, Croatia is currently in the process of its preparation and public consultation. In this way, MSP (maritime spatial planning) could serve as an instrument linking national spatial policies with European objectives and regional cooperation initiatives, creating a framework for sustainable and integrated management of the entire Adriatic area.

The area covered by the marine surface is divided into the territorial sea areas of the counties, which are linked to county authorities in the adoption of spatial plans, and the spatial plan of the exclusive economic zone, for which the competent Ministry is responsible (Figure 2) .

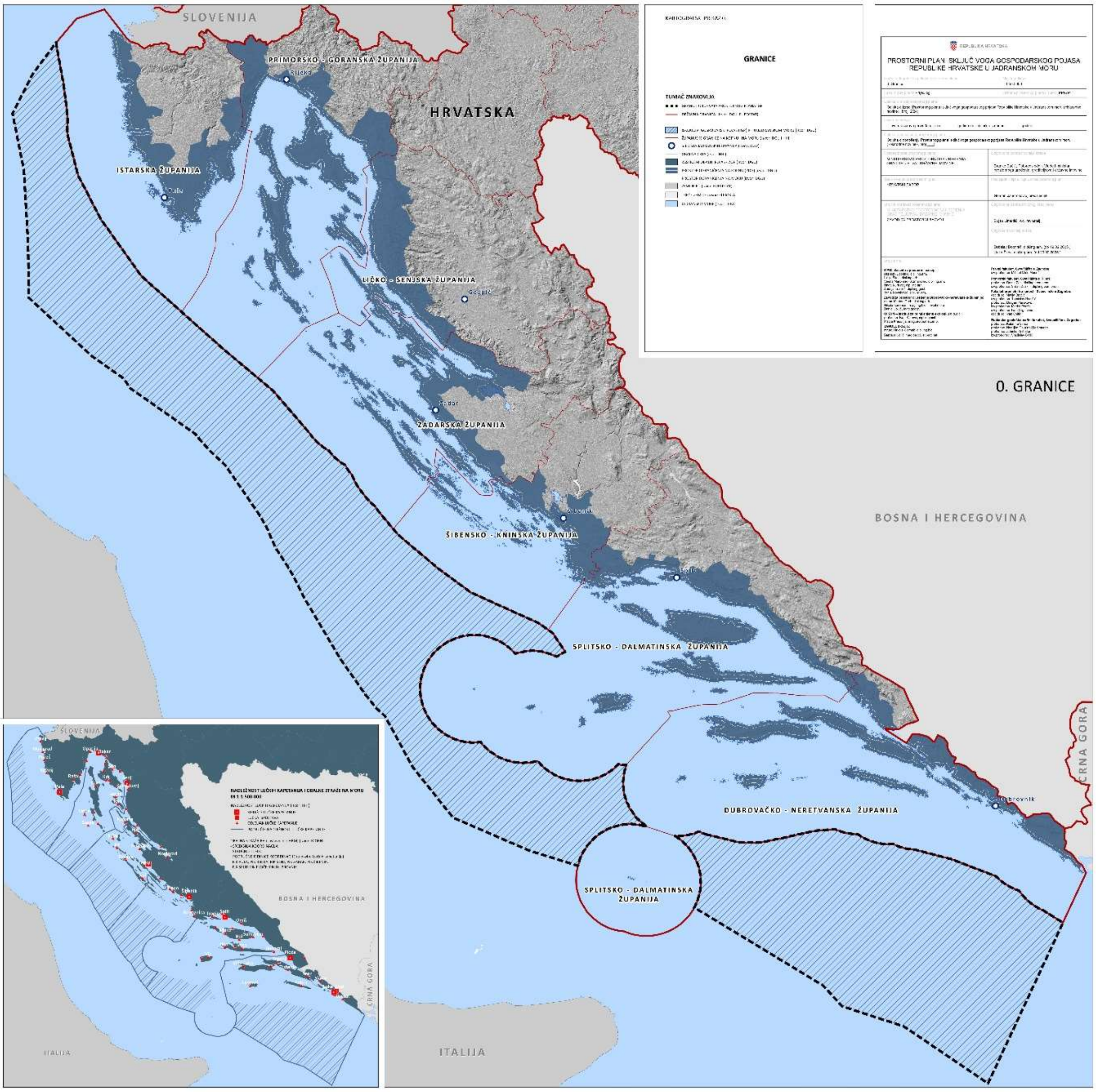

Figure 2 Counties jurisdiction overview of in the territorial sea and the extent of the exclusive economic zone

3.3. Development of Pilot Areas from the Perspective of Spatial Planning in Croatia

For the time being, according to the available draft of the Spatial Plan for the Exclusive Economic Zone (https://mpgi.gov.hr/vijesti-8/objava-javne-rasprave-o-prijedlogu-prostornog-plana-iskljucivog-gospodarskog-pojasa-u-jadranskom-moru/18685), no offshore wind farms or green hydrogen production are foreseen within the Exclusive Economic Zone.

However, the areas designated as pilot areas in this analysis – consisting of two polygons, one in Istria County and the other in Split-Dalmatia County – are located within the territorial sea. Therefore, the provisions of the Spatial Plan for the Exclusive Economic Zone do not apply to these polygons.

In the area of Split-Dalmatia County, within the territorial sea, the spatial plan does not foresee infrastructural projects related to energy, whether conventional or renewable. It is important to note that such projects are not explicitly excluded; however, the plan makes no reference to renewable energy sources at sea, thus lacking a strategic orientation towards their development. In the textual part of the plan, specifically in Article 163, a commitment to the construction of wind farms and the promotion of renewable energy sources is stated. The programme for the use of RES (renewable energy sources) is emphasised as being of particular importance due to the abundance of resources and favourable ecological conditions in the county, as well as the technical and technological advantages of the energy conversion process. However, all designated locations for wind farms are situated exclusively on land; no locations are foreseen at sea. Thus, the potential for developing offshore renewable sources remains to be addressed in future steps. Moreover, hydrogen is not mentioned at all – neither in the context of production, transport, nor as part of the broader energy strategy within the county. Such a spatial plan, although it refers to renewables in a general sense, does not provide a developed vision for the maritime energy sector and therefore also not for the development of new infrastructure required for the production and distribution of green hydrogen. In other words, it neither recognises nor supports the development of technologies identified at the EU level as key for the transition to climate neutrality. For this reason, further steps are expected towards the adoption of both European and national guidelines, strategies, and binding acts covering this technology.

Furthermore, regarding aquaculture, the plan designates areas intended for aquaculture along the coast, including the Kaštela Bay. These areas are located outside the planned pilot sites of this project; therefore, there is no direct conflict between aquaculture zones and the potential development of the project's energy initiatives.

However, according to an analysis of the spatial plan maps of the Split-Dalmatia County spatial plan, it can be observed that no restrictions have been mapped which could be associated with the development of offshore wind farms, hydrogen infrastructure, or open-sea aquaculture activities (Figure 3 and Figure 4).

Although the spatial plan itself does not foresee the use of offshore wind energy, the county has adopted the Implementation Programme of Split-Dalmatia County for the period 2022–2025, in which energy transition is recognised as one of the key development priorities. In measure PC 3.3, the need for a stronger reliance on renewable energy sources is emphasised, particularly given the exceptional solar and wind potential in this area. The county places special emphasis on projects that contribute to reducing greenhouse gas emissions, increasing energy efficiency, and strengthening local energy self-sufficiency.

According to the Programme, the energy transition is not viewed solely in a land-based context but also as part of the broader concept of blue energy. It highlights the potential of the sea and the coast as sources of clean energy, thereby opening possibilities for the future integration of green hydrogen production based on renewable energy within the county.

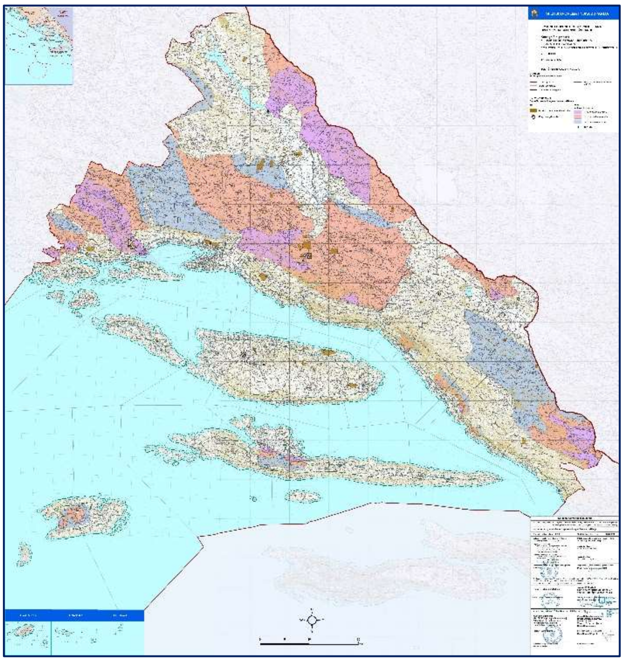

Figure 3 Areas of Special Restrictions in Split-Dalmatia County

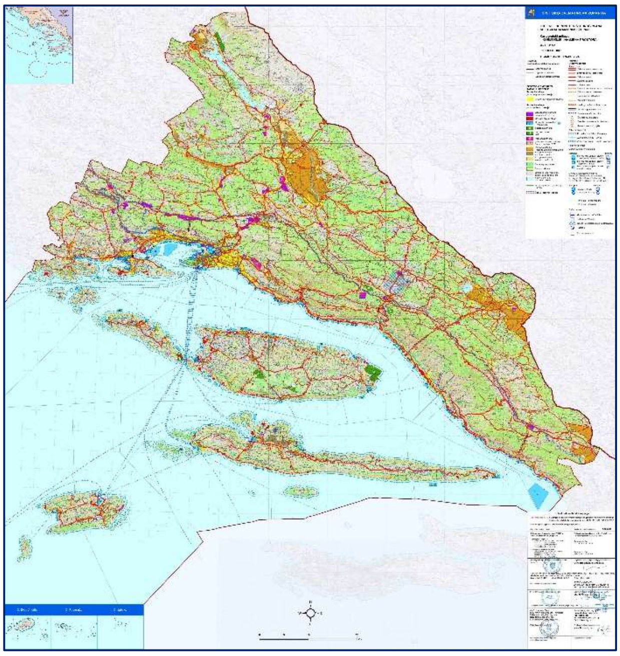

Figure 4 Land Use and Spatial Designation in Split-Dalmatia County

A very similar situation exists in Istria County. The valid spatial plan explicitly refers to the use of wind energy and sets out certain restrictions for selecting sites for the construction of wind farms. However, based on the content and the way these conditions are formulated, it can be concluded that they primarily apply to onshore wind farms, while the question of the potential development of offshore wind farms is not addressed, even though this technology could have significant potential on the Istrian peninsula.

In addition, it should be emphasised that hydrogen is not mentioned at all – neither in the context of production nor in transport. This points to a lack of a strategic approach to planning the integration of new technologies into spatial development, which contrasts with current European energy policies that highlight the importance of green hydrogen as a key energy carrier in the transition towards climate neutrality.

An analysis of the spatial plan maps shows that within the territorial sea of the Republic of Croatia, around Istria County, there are no polygons designated for the development of wind farms (Figure 5 and Figure 6). Areas intended for aquaculture are predominantly located in the coastal zone, which also reflects a conservative approach to planning maritime activities. The only exception is one polygon located along the western coast of Istria; however, it is situated relatively close to the shore and does not interfere with the proposed pilot areas of this project. For the further development of renewable energy sources and green hydrogen production, it is essential to integrate these elements into spatial plans. This would enable alignment with European hydrogen production priorities and lay the foundation for a sustainable and competitive energy transition in Istria County.

In conclusion, based on the existing legislative and strategic framework, it can be stated that both Istria County and Split-Dalmatia County possess the energy potential and formal prerequisites to include zones for the development of offshore wind farms and green hydrogen production facilities in their spatial plans, provided that such development is aligned with maritime domain regulations and the concession framework, and coordinated with national plans and the competent Ministries.

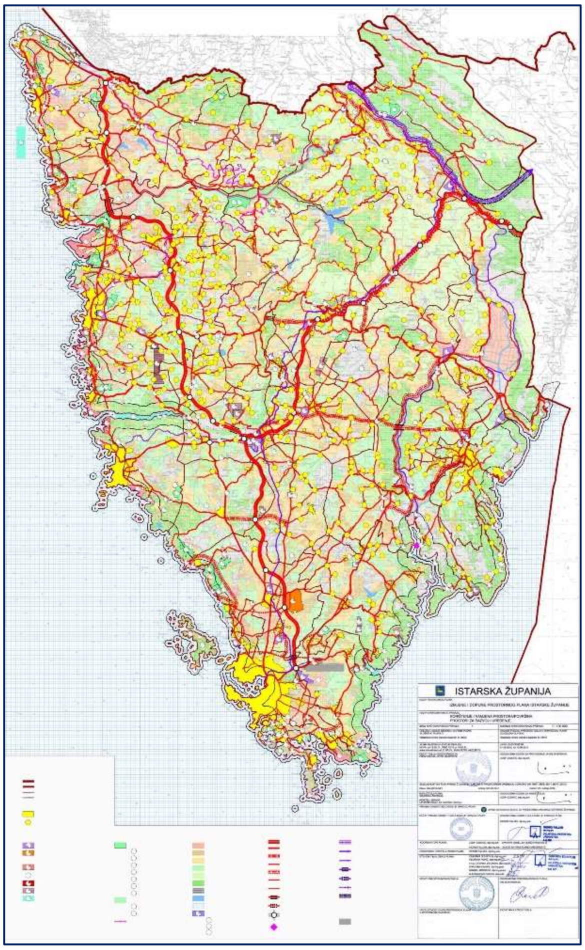

Figure 5 Areas for Development and Planning in Istria County

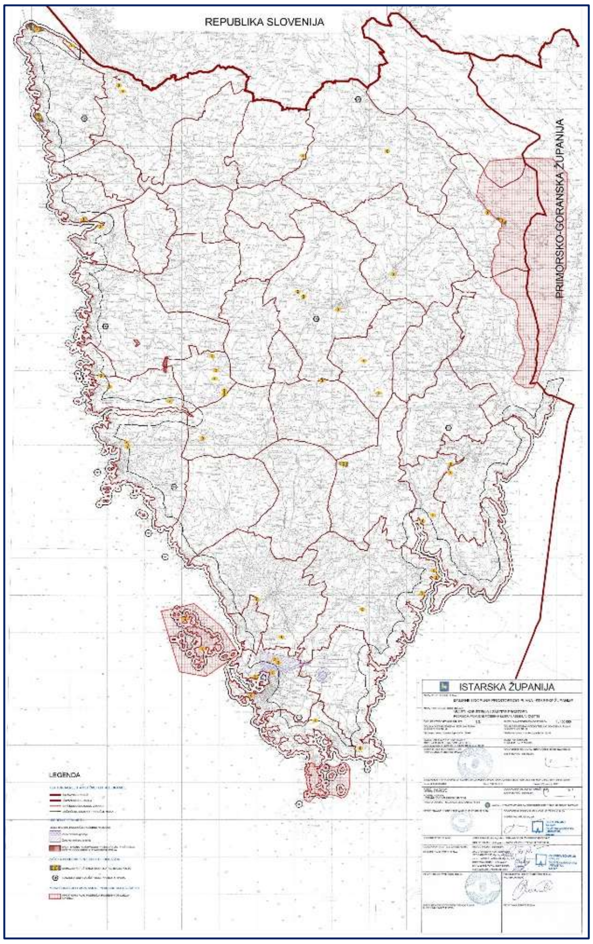

Figure 6 Areas under Special Planning and Protection Measures in Istria County

In the field of spatial planning, in line with the MSP Directive, several joint dialogue initiatives have been launched between Italy and Croatia through the Interreg Italy–Croatia programme.

The most significant of these is the SHAPE project – *"Shaping a Holistic Approach to Protect the Adriatic Environment between coast and sea."* Within the project, one of the key work packages (WP4) was entirely dedicated to the development of maritime spatial planning (MSP). Its goal was to support MSP in the Adriatic basin through the development of a specific methodology for planning, joint data processing and mapping, and testing of approaches through the implementation of pilot actions at regional and local levels.

This cross-border cooperation had broader objectives: strengthening sustainable blue growth, promoting integrated maritime spatial planning, creating a platform for knowledge exchange, and fostering regional cooperation in addressing challenges and seizing new opportunities in the Adriatic.

In addition to SHAPE, the InnovaMare Project is also one of the Interreg Italy–Croatia projects, aimed at enhancing cooperation in technology transfer through a network for underwater robotics and sensors. Although it does not focus explicitly on MSP, this project contributes to strengthening technical capacities and innovation infrastructure in the marine sector. The same applies to several other projects under the Interreg Italy–Croatia 2021–2027 Programme, which prioritises *Sustainable Growth in the Blue Economy*.

3.4. Legislative Framework for the Development of Hydrogen Technologies in Italy

The regulatory situation for hydrogen in Italy is complex due to the large number of central, regional, and local authorities that currently play decisive roles in approving any potential hydrogen project, as well as offshore wind farm projects. It is evident that Italy has ambitious plans for hydrogen, promoting the development of hydrogen valleys in industrial and port areas, hydrogen production in brownfield sites (including coastal areas), and investments in infrastructure, research, and public–private partnerships. However, despite the adoption of a national strategy and other legislative acts, Italy currently does not have specific legal provisions or technical guidelines regulating hydrogen production at sea.

The term hydrogen first appeared in 2016 in Legislative Decree of 16 December 2016, No. 257 (Il Decreto Legislativo 16 dicembre 2016, n. 257), which transposed into Italian law *Directive 2014/94/EU on the deployment of alternative fuels infrastructure (AFID)*. The Decree sets out rules for the development of alternative fuel infrastructure in Italy, creating a regulatory and strategic framework for building a network that enables the use of alternative fuels in transport – including electricity, natural gas, liquefied petroleum gas (LPG), and hydrogen – with the aim of reducing dependence on oil and the environmental impact of the transport sector. The Decree defines minimum requirements for electric vehicle charging stations and refuelling stations for natural gas, hydrogen, and LPG, encouraging public access and the sharing of user information. It stipulates that refuelling stations must be built at strategic locations, primarily along the TEN-T corridors and in major urban centres, in full compliance with European technical standards and safety requirements. The aim is to achieve interoperability and interconnection of the national network with the infrastructure of other Member States. The Decree also provides for financial instruments and incentives to promote investment in hydrogen refuelling station (HRS) infrastructure, including public funds and European programmes, as well as attracting private investment. In this way, the Decree not only introduces hydrogen into the national legal framework for alternative fuels but also positions it as one of the key solutions for the future development of sustainable transport and for Italy's energy transition.

A further step in promoting development and creating the framework and prerequisites for the production of green hydrogen was the adoption of the Ministerial Decree on technical rules for the design, construction, and operation of hydrogen distribution facilities for motor vehicles in 2018.

In December 2019, Italy published its Integrated National Energy and Climate Plan (PNIEC), setting out plans to 2030 in line with the goal of achieving full decarbonisation of the energy sector by 2050. In this document, hydrogen is mentioned several times, although it did not contain detailed plans or concrete numerical targets for hydrogen development. However, the plan set a target of a 30% share of renewables in gross final consumption by 2030. Subsequently, in November 2020, Italy finally published the introduction to its national hydrogen strategy in the form of the *Preliminary Guidelines for the National Hydrogen Strategy (*Strategia Nazionale Idrogeno – Linee Guida Preliminari*)*, which already proposed a target of 5 GW of electrolyser capacity by 2030. It was expected that the approach to hydrogen development would be further elaborated during 2021 as part of the country's plans to achieve climate neutrality by 2050.. The Guidelines focus on transport and industry as the leading sectors for hydrogen application, while also mentioning power generation and the potential blending of hydrogen with natural gas in the grid.

In recent years, Italian legislation has increasingly focused on the integration of renewable energy sources and new energy vectors into the national system, with hydrogen being ever more clearly recognised. Its role is described in Legislative Decree No. 199 of 8 November 2021 (Decreto Legislativo 8 novembre 2021, n. 199*)*, which transposes the RED II Directive. Several articles highlight the role of hydrogen; for instance, Article 11 emphasises the importance of incentives for the production and injection of biomethane into the natural gas grid through a dedicated tariff. Although this mechanism was primarily designed for biomethane, it also opens the way for the future by foreseeing the possibility of extending incentives to the production of gaseous fuels from renewable non-biological sources – namely, green hydrogen produced using energy from offshore wind farms. In this way, the foundations are laid for financial support for green hydrogen production and its integration into the energy system. Further emphasis on infrastructure is provided in Article 35, which addresses the acceleration of electricity grid development to accommodate the growing share of renewable energy needed to achieve energy transition goals. It requires grid operators to plan, based on the projected increase in renewable energy generation, and to ensure timely connections and the necessary infrastructure, including networks for electric vehicle charging. The importance of urgent grid interventions is particularly highlighted, with emphasis also placed on offshore technologies, which will be a prerequisite for future green hydrogen production projects at sea.

Linked to this is Article 36, which regulates the measurement system and the allocation of incentives for renewable energy. It establishes the obligation to collect and verify data on electricity generation to ensure accuracy, transparency, and timeliness in the disbursement of incentives. Such transparency is also crucial for the future development of the renewable hydrogen market, as its sustainability and certification will depend on a clear system of monitoring and reporting. Article 37 further strengthens the role of renewable gases by foreseeing the optimisation of plant connections to the gas grid. Although it primarily concerns biomethane, it is explicitly stated that the rules also extend to other types of renewable gases, including hydrogen, whether pure or blended. This opens the possibility for the gradual integration of hydrogen into existing gas networks, which is important for the transitional period in which hybrid solutions with gas–hydrogen blends may be used. Finally, Article 46 introduces provisions on the system of guarantees of origin (*Garanzie di Origine*), which are foreseen not only for electricity and biomethane but also for hydrogen, thereby confirming its status as a key energy vector. The introduction of guarantees of origin for hydrogen provides additional transparency, traceability, and proof of its sustainability – which is essential for market development and attracting investment.

At the national level, hydrogen development in Italy is supported through the Italian National Hydrogen Strategy and through implementation plans under the Piano Nazionale di Ripresa e Resilienza (PNRR), which are also considered the main framework documents for hydrogen. The Plan was adopted in 2021 but was later updated in 2022 and 2023, precisely to include a chapter dedicated to REPowerEU, with a strong focus on renewable energy and hydrogen.

In the Italian National Recovery and Resilience Plan (PNRR), hydrogen is clearly recognised as a strategic energy carrier of the future and one of the key tools in the transition towards climate neutrality. The document emphasises that without the widespread use of hydrogen, Italy cannot achieve its decarbonisation goals in sectors where electrification has limited potential – particularly in heavy industry such as steelworks, the chemical sector, and refineries, as well as in long-distance transport, where alternative fuels are still at an early stage of development. The concrete plans foresee the installation of 5 GW of electrolyser capacity by 2030, enabling significant production of renewable, so-called green hydrogen. Special emphasis is placed on the development of so-called *hydrogen valleys*, i.e. energy hubs in abandoned industrial areas, where renewable hydrogen would be produced and consumed locally. In this way, the revitalisation of neglected regions is combined with the development of new industrial and energy infrastructure. In the transport sector, the PNRR foresees the deployment of a network of 40 hydrogen refuelling stations, primarily intended for heavy-duty vehicles, to encourage their gradual introduction along major transport corridors. In addition to road transport, the plan also covers the railway sector, through the conversion of non-electrified lines, for example, in Lombardy, Sicily, and Puglia, to hydrogen-powered trains. Specifically, in Chapter 3.4 *"Sperimentazione dell'idrogeno per il trasporto ferroviario"*, the plan foresees the conversion of certain parts of the railway network, namely six non-electrified lines, to hydrogen traction, along with the establishment of nine hydrogen refuelling stations for trains on those lines as concrete infrastructural targets. Through this, Italy aims to reduce dependence on fossil fuels in areas where conventional electrification is not cost-effective or technically feasible. In addition to these figures, Italy also plans to support 52 projects/hubs for green hydrogen production, with half of them located in the southern regions of Italy, primarily in abandoned industrial zones (*brownfield sites*). The PNRR does not limit its vision to infrastructure and production but strongly emphasises the importance of research and development. Dedicated funding is foreseen for the development of advanced technologies such as high-pressure and high-efficiency electrolysers, innovative hydrogen storage solutions, and fuel cells for different sectors of application. The aim is to foster the creation of an Italian and European hydrogen value chain, from research and development to industrial application and international trade. In the long term, Italy's objective is for renewable hydrogen to become a fundamental energy carrier by 2050, with a share of at least 20% of total energy consumption. This would ensure the decarbonisation of key sectors, stabilisation of the electricity system through energy storage, and strengthening of the country's energy security. A particular ambition of Italy is to become a regional hub for hydrogen production and distribution, thanks to its geostrategic position in the Mediterranean and its connection to future supply corridors from North Africa to Central Europe. Ultimately, the PNRR places hydrogen at the core of Italy's energy transition, linking climate goals with industrial development and strengthening the country's international role. This creates a framework not only for reducing emissions but also for opening new markets, innovation, and jobs in the context of a sustainable future. These objectives have been taken up by the Italian National Hydrogen Strategy adopted in 2024 (La Strategia Nazionale sull'Idrogeno (SNI) italiana), which likewise defines hydrogen as a key energy carrier in the green transition, with ambitions to develop the capacities, infrastructure, and technological solutions needed to achieve significant emission reductions, strengthen energy independence, and enhance industrial competitiveness. The Strategy is aligned with the national energy plan and the declared EU objectives, and its implementation foresees concrete steps in the period up to 2030 and 2050. The main quantitative target is the installation of at least 5 GW of electrolyser capacity by 2030 and the production of 0.7 Mtep of hydrogen, which should enable renewable hydrogen to secure a significant share of energy consumption, with estimates suggesting it could cover around 2% of Italy's final energy consumption by then. The Strategy foresees the establishment of so-called *hydrogen valleys,* local areas where hydrogen production and consumption take place within a narrow geographical and infrastructural framework, aimed at creating pilot models for the local integration of hydrogen into industrial and transport sectors. A further plan includes the expansion of both domestic and cross-border infrastructure, as well as greater market uptake of hydrogen in various applications, such as heavy industry and transport. or the first period, from 2030 to 2040, the Strategy foresees the expansion of capacity, increased production, and wider use of hydrogen in the industrial, transport, and energy sectors, with an emphasis on infrastructure for distribution and storage. By 2050, hydrogen is expected to become a common energy carrier in heavy transport and industry, with its role extending also to power generation, energy storage, and stabilisation of the electricity system. In this context, the share of hydrogen in final energy consumption could reach 20% or more, depending on the scenario. The Strategy also announced the adoption of a national plan for the development of a hydrogen refuelling station network by 2027, in response to EU regulation (AFIR), which requires one station every 200 km along the TEN-T network, with a capacity of at least 1 tonne of H_2 per day at 700 bars.

The Strategy outlines several scenarios (Figure 7), among which the so-called ***high*** scenario assigns this vector a very important role, although in all cases it leaves considerable space, varying from sector to sector, for other options. This scenario foresees the accelerated and widespread deployment of hydrogen in the economy. In this case, by 2030 Italy plans to reach at least 5 GW of electrolyser capacity and secure a significant share of renewable hydrogen in the energy mix. This includes rapid infrastructure development, intensive investments, the promotion of domestic production, and the establishment of cross-border supply chains, laying the foundation for the large-scale use of renewable hydrogen. In this scenario, hydrogen becomes a key energy carrier for the decarbonisation of heavy industry, transport, and the energy system, while Italy positions itself as a regional hub for renewable hydrogen production and distribution. In the period 2030–2040, the plan foresees the expansion of production capacities, the development of transport and storage infrastructure, and the integration of hydrogen into the energy system. By 2050, under this scenario, hydrogen becomes a key energy carrier with a share of 20% or more in total energy consumption, fully integrated into industry, transport, power generation, and storage systems. In this case, Italy positions itself as one of Europe's hubs for green hydrogen production and distribution, relying both on domestic resources and on cross-border supply corridors, particularly towards the Mediterranean and North Africa.

The *baseline* scenario, on the other hand, still recognises hydrogen's significant contribution but represents a more conservative approach. It assumes greater delays in the maturity and competitiveness of this vector, possibly also in the presence of policies and socio-economic conditions that favour other options.

In this scenario, the emphasis is placed on launching pilot projects, limited application in industry, and the first demonstration solutions in transport. At this pace, by 2030 hydrogen would hold only a modest share of total energy consumption, with the focus being on the creation of a regulatory and infrastructural framework. During the period from 2030 to 2040, expansion continues, but hydrogen largely remains only a complementary energy carrier. It is only by 2050 that hydrogen, under this scenario, reaches a moderate share of total energy consumption (estimated at 10–12%), with its role limited to specific hard-to-decarbonise sectors such as the chemical industry, steel production, and parts of the transport sector.

The *medium* scenario represents an intermediate situation between the previous two.

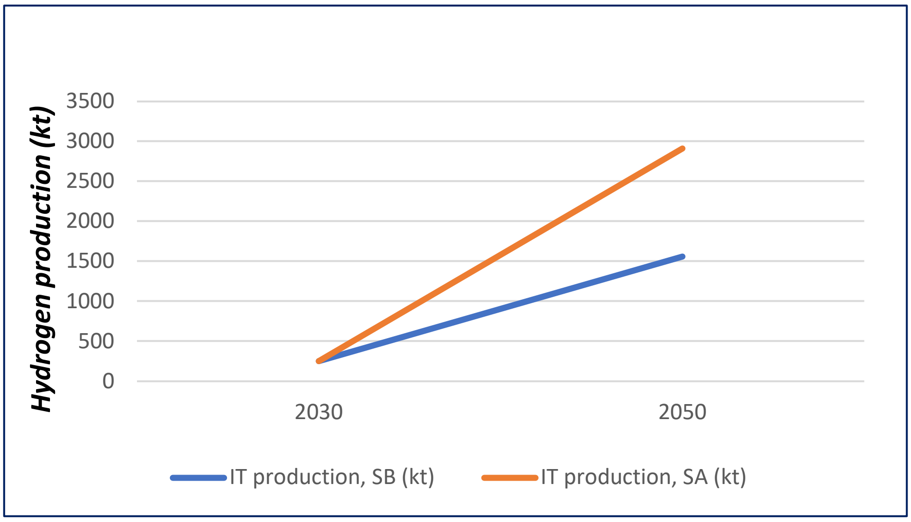

Figure 7 Hydrogen consumption in Italy (kt) under two scenarios; SB baseline, SA high

The Emergency Provisions for the Implementation of the National Recovery and Resilience Plan (NRRP) and the National Investment Plan complementing the NRRP (Decreto-Legge 24 febbraio 2023, n. 13) were adopted in 2023. These provisions introduce simplifications in procedures related to green and renewable hydrogen. Article 41 provides key clarifications to promote the development of green and renewable hydrogen projects: priority is given to projects related to the production of green or renewable hydrogen, as well as to associated renewable energy facilities, in environmental impact assessment (EIA) procedures. Moreover, production plants integrated within industrial facilities for large-scale hydrogen production are now explicitly included among projects of public interest carried out under the National Energy and Climate Plan (PNIEC), and all simplifications of administrative procedures apply to them. This means that green hydrogen production projects are prioritised in EIA procedures, thereby accelerating administrative processes and reducing bureaucratic barriers, often key challenges in programmes such as the PNRR. In addition to simplifying procedures, this document is the first to explicitly grant public interest status to green hydrogen projects, link them with key PNRR investments, and open access to additional funds (cohesion, regional development).

3.5. Development of pilot areas from the perspective of spatial planning in Italy

In addition to the regulatory framework for the production, transport, and use of green hydrogen, it is also necessary to "reserve" spatial areas for hydrogen infrastructure. As in Croatia, Italy, as an EU Member State, is obliged to adopt and implement the MSP Directive on maritime spatial planning. The beginning of this process in Italy was marked by the publication of the Decree of the President of the Council of Ministers (DPCM) *(Linee guida per la predisposizione dei piani di gestione dello spazio marittimo*) or Guidelines for the preparation of maritime space management plans of 1 December 2017, which contains the official guidelines and criteria for the development of maritime spatial management plans. The guidelines define the methodological framework, stakeholder involvement approach, integration with existing spatial plans, and the model for monitoring and revision of the MSP plan. Three main maritime zones were identified for MSP planning: the Western Mediterranean, the Adriatic Sea, and the Ionian/Central Mediterranean. The guidelines are aimed at establishing an overarching plan that coordinates all sectoral plans related to marine and coastal areas, sustainable development, and the balanced use of marine resources such as aquaculture, mining, transport, renewable energy, and stakeholder involvement, while ensuring planning consistency and legal certainty. In addition to the main zones, the area is further divided into sub-zones in order to ensure a more effective approach to the sustainable planning of the marine space (Figure 8).

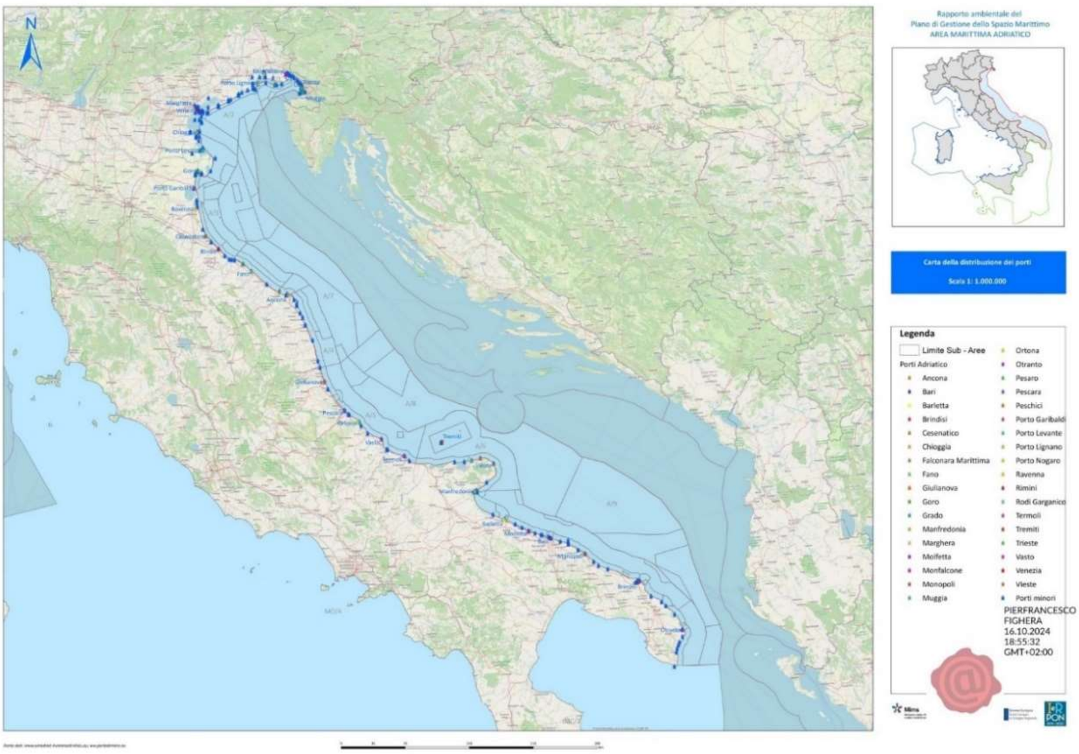

Figure 8 Division of the main zone of the Adriatic Sea into subzones. Source: https://sid.mit.gov.it/documenti-piano

Following the adoption of the guidelines, of the Strategic Environmental Assessment (SEA) and the assessment of impacts on the Adriatic maritime area, in 2024 the Italian Maritime Spatial Management Plan (*Piano di gestione dello spazio marittimo Italiano*) was approved. The documents are available through the Ministry of Infrastructure and Transport (https://www.sid.mit.gov.it/documenti-piano).

The plan is strongly focused on energy development, with an emphasis on the production of energy from marine renewable sources, including the identification of the most suitable areas for the installation of facilities. At the same time, the plan addresses ecological, social, and economic sustainability by identifying maritime areas suitable for CO_2 capture and geological storage, and by defining a framework for exploration, prospecting, and hydrocarbon production.

Among the specific objectives relevant to this project, *SC 1* stands out, which entails promoting the energy transition towards renewable and low-emission sources by developing offshore renewable energy production. Furthermore, *SC 3* emphasizes the repurposing of existing platforms and infrastructures related to depleted fields, including the development of synergies between different activities.

The Adriatic Sea plan further emphasizes the need to adopt national guidelines for the identification of suitable offshore renewable energy sites (wind, solar, wave, and tidal), which should enable the assessment of both individual and cumulative impacts on the environment, landscape, and cultural heritage, covering all phases from construction and operation to decommissioning of installations. The guidelines must also consider the infrastructure required to transport the generated energy to the mainland. These guidelines are expected to significantly accelerate and improve spatial planning of sub-zones within the Adriatic Sea, facilitate the design of installations, and streamline the permitting process (e.g., EIA procedures).

Within the accompanying documentation *Azioni future - Appendice I - Valutazione Ambientale Strategica*, the preparation of a preliminary study for the Ministry of Environment and Energy Security (*MASE*) is foreseen, with the aim of identifying the most suitable areas for the development of offshore wind farms. This study will consider existing activities and research, the environmental sensitivity of specific areas, the definition of suitable/unsuitable zones from an environmental perspective, the renewable acceleration areas defined by Directive (EU) 2023/2413, as well as existing authorization requests and grid connection applications to the national transmission system. At the same time, it will be aligned with the national energy production targets for 2030 and 2050.

A particularly important section of the plan is found in *Appendice III - Valutazione Ambientale Strategia*, which emphasizes the contribution of maritime spatial plans to the energy transition towards renewable and low-emission sources. The plan is defined as a tool for decarbonizing the economy, reducing emissions, and promoting energy production from marine renewables. In addition, it highlights its role in fostering sustainable mobility of people and goods, as well as promoting resource-efficient aquaculture. The plan is primarily environmentally oriented while at the same time representing a key instrument for implementing the offshore energy transition, especially for testing and deploying technologies such as offshore wind farms. *Appendice III* also stresses the need to plan pipelines to the mainland, for example for transporting green hydrogen produced offshore. The document further underscores the importance of coordinating onshore and offshore activities, including the conversion of existing industrial areas into sites for construction, assembly, and maintenance of infrastructure necessary for receiving offshore-generated energy. It also recognizes the necessity of planning for increased maritime traffic related to the construction and operational phases of new installations.

In areas where hydrocarbon infrastructure already exists, the plan recommends repurposing platforms for multipurpose projects, including storage of renewable energy (e.g., hydrogen), the creation of biological protection areas, and their use for tourism, underwater fishing, and aquaculture. Beyond practical measures, the plan also encourages research and experimental initiatives focused on renewable energy, innovation in the hydrogen sector, and the reuse of decommissioned platforms for scientific, aquaculture, and tourism purposes.

In conclusion, the spatial plan for the Adriatic Sea does not yet designate concrete locations for future offshore wind farms and hydrogen installations—these will be defined within sub-plans for individual subzones. Nevertheless, it clearly sets out environmental restrictions that must be respected. For example, the cartographic annexes indicate areas with minimal protection constraints (grey), areas with a high share of protection (red/orange), and those where reconciling new projects with environmental conservation and fisheries will be most challenging. In other words, they illustrate how much of the Italian Adriatic is already “occupied” by various protection regimes and levels of restriction (Figure 9).

The map analysis shows that in the northern Adriatic (Veneto, Emilia-Romagna) protection coverage is relatively low (up to 15%), while the central Adriatic (Marche, Abruzzo) is characterized by fishing zones with higher levels of protection. The southern Adriatic (Puglia) stands out with areas of increased protection (ranging from green to orange), including zones where protection levels exceed 30%.

However, when reviewing the map, the pilot polygons identified for this project are in the Veneto and Puglia zones, where the share of protected areas is generally below 1%. Nevertheless, for an accurate assessment, it is necessary to “overlay” all layers and coordinates of pilot polygons within a GIS system.

In addition, the spatial plan and the accompanying strategic study also provide an overview of the existing infrastructure and its relationship to protected areas, for example, they illustrate the current interaction of offshore wind farms with bird migration routes (Figure 11). The maps indicate where these impacts are high and therefore pose risks, and where they are low or negligible. It is particularly important to emphasize that migration routes represent a critical factor in the permitting process for offshore wind farms and the associated production of green hydrogen, making this information crucial for investors (Figure 10).

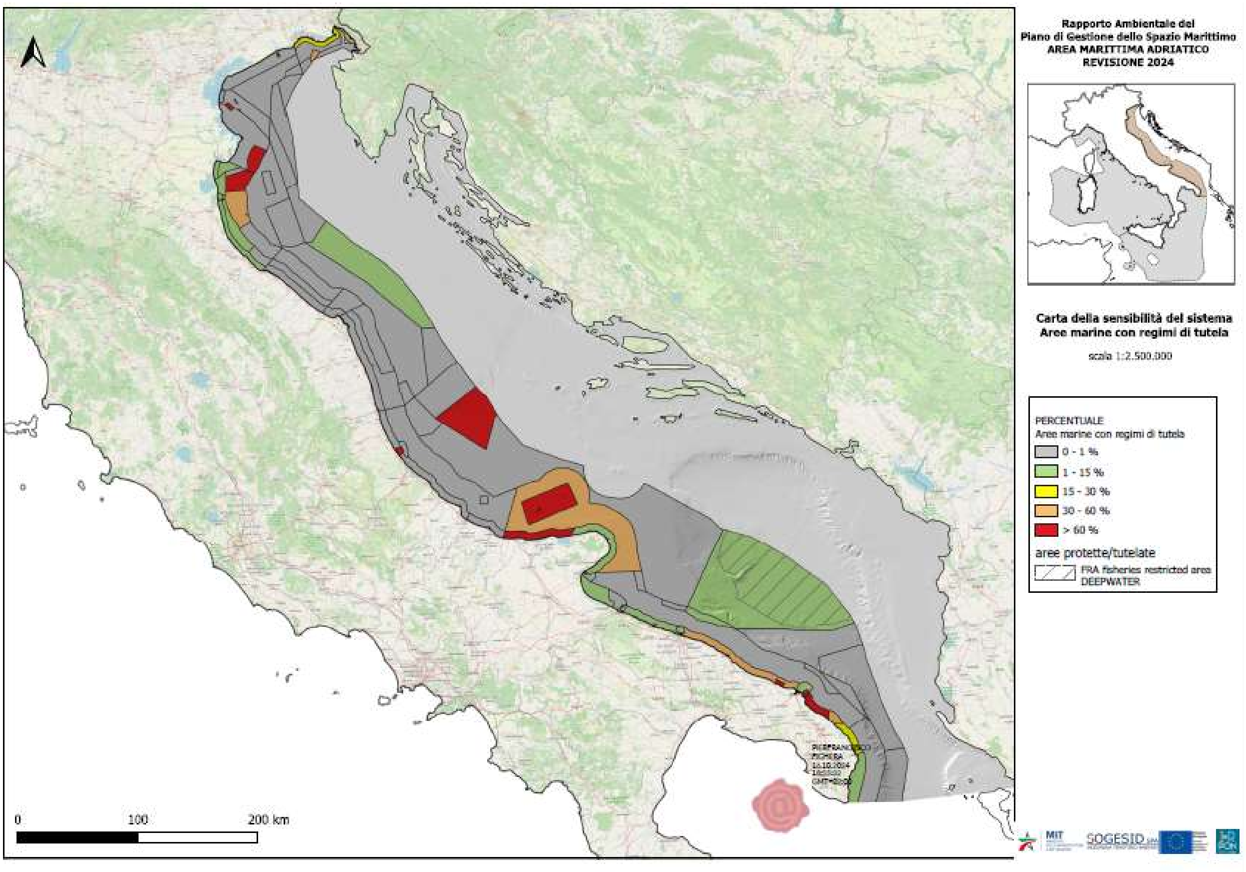

Figure 9 Protected areas in the Adriatic Sea zone (colours indicate the share of protected surfaces within a given segment of the coastal sea). Source: https://sid.mit.gov.it/documenti-piano

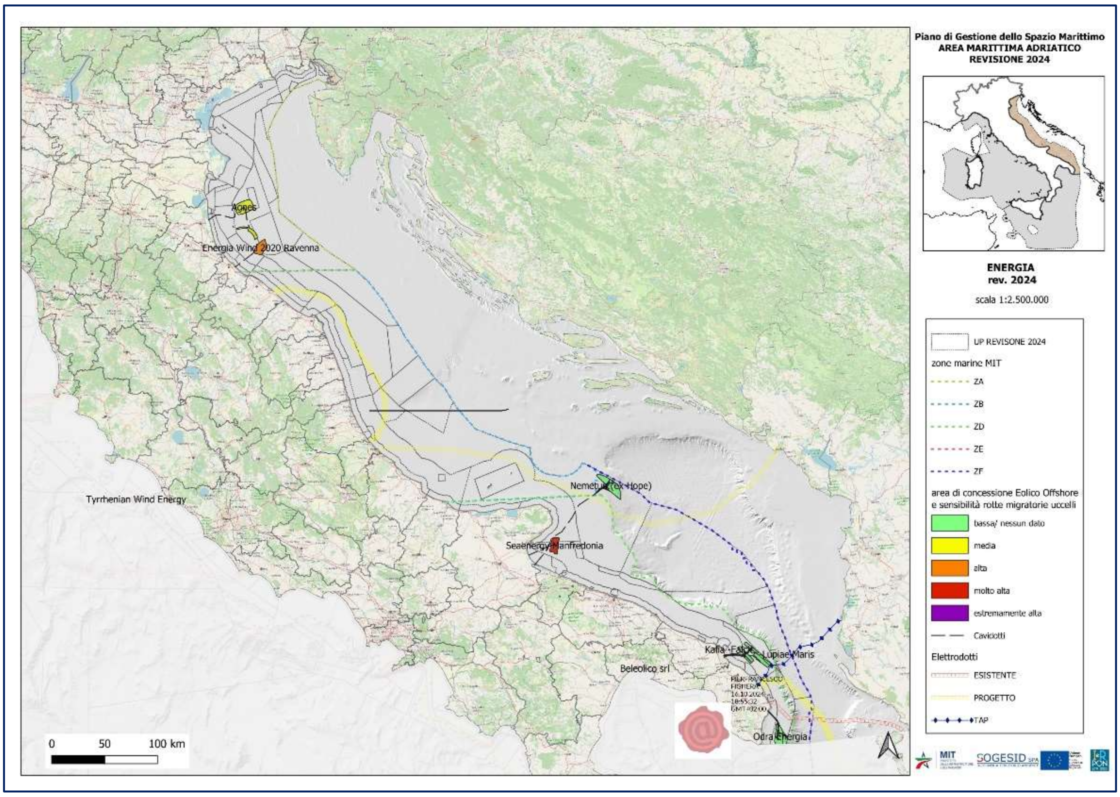

Figure 11 Combination of offshore wind farm areas, power cables, and bird migration routes. Source: https://sid.mit.gov.it/documenti-piano

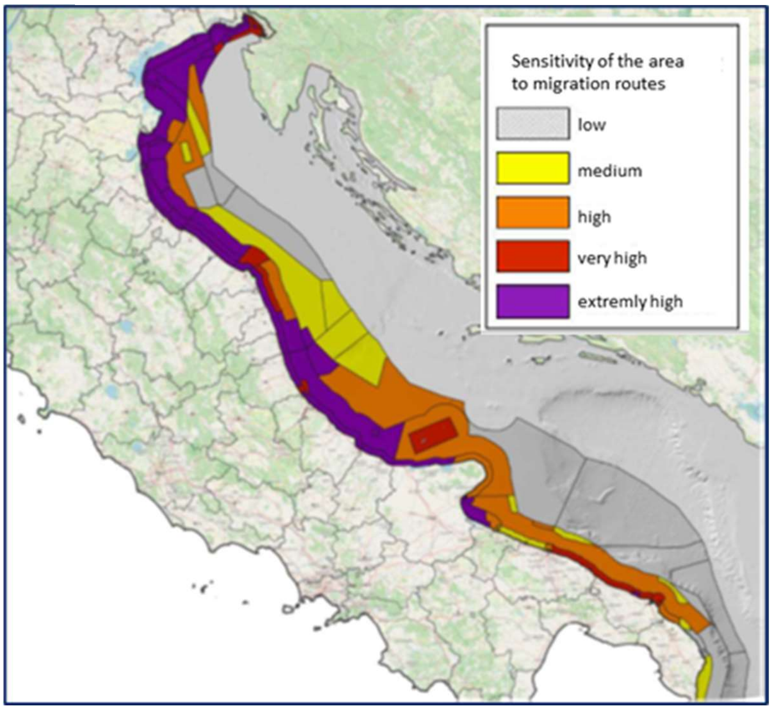

Figure 10 Overview of the Adriatic Sea zone and its relation to bird migration routes. Source: https://sid.mit.gov.it/documenti-piano

In this project, several pilot areas are planned, specifically a total of five sites. Two sites are located in the northern part of Italy, in the Veneto region, and form a connected unit, while the remaining three are situated in the southern part of Italy, in the Puglia region, where they are also grouped into a single unit.

According to the Italian Maritime Spatial Management Plan (*Piano di gestione dello spazio marittimo Italiano*) (https://www.sid.mit.gov.it/documenti-piano), two smaller polygons are located within the territorial waters of the Italian Republic, in the area designated as A/6, while the largest polygon is situated within the Exclusive Economic Zone of the Italian Republic, in area A/9 (Figure 13). In area A/6, the main uses of the sea include coastal and maritime tourism, maritime traffic and related port activities, fisheries, environmental and natural resource protection, landscape and cultural heritage conservation, as well as activities connected to national defence. In addition, for this area, the Plan specifically highlights the need to foster research on the sustainable use of wave energy, the transformation of ports into facilities with a positive energy balance, the reduction of CO_2 emissions and other pollutants associated with the combustion of fossil fuels in port activities, and recommendations for aligning the protection of marine and coastal habitats, landscape, and visual integrity with innovative forms of renewable energy production. As an example, the development of offshore wind farms on existing and decommissioned platforms, which would be integrated into the green hydrogen production chain, is mentioned. The two smaller polygons located within subzone A/6 entirely encompass sub-units A/6_10 and A/6_13, which are marked with the letter G, indicating their general purpose of use. Accordingly, within the pilot polygons in this area, it is possible to plan renewable energy production, provided that proper planning and correct positioning of onshore units are ensured (Figure 12). The remaining polygons are in subzone A/9. In this marine area, the main uses of the sea include maritime traffic, fisheries, environmental and natural resource protection, landscape and cultural heritage conservation, hydrocarbon exploration and exploitation, as well as activities connected to national defence. It is particularly emphasized that this area encourages experimentation and broader application of offshore renewable energy production technologies, with special focus on wind energy, in accordance with the prevailing environmental and landscape protection policies (Figure 13). Furthermore, it can be observed that the marine area designated for the project activities, i.e., the pilot area, fully encompasses the sub-area A/9_01 – G, also classified under general use (Figure 12)) (*Piano di gestione dello spazio marittimo Italiano – Area Marittima "Adriatico" Rapporto Ambientale, Valutazione Ambientale Strategica*[1]*, Valutazione di Incidenza*). Accordingly, within this pilot polygon it is also possible to plan renewable energy production, provided that proper planning and positioning of onshore units are ensured. Both areas, in addition to the fact that all polygons fall within zones marked with G (general use), are also located in areas where the sensitivity rate of protected marine systems is the lowest, ranging between 0–1%, which will facilitate the permitting process and the placement of units at sea (Figure 8). At the same time, for polygon A/6, it is indicated that suitable areas for sustainable aquaculture, designated for agricultural purposes, as well as the necessary service areas for this activity, still need to be defined, whereas such an activity is not foreseen for polygon A/9.

Both pilot areas, both northern and southern, are also characterized by a favourable distribution of coastal ports that can support future activities related to the development and implementation of energy projects (Figure 14).

[1] VAS is Italian name for SEA or Strategic Environmental Assessment

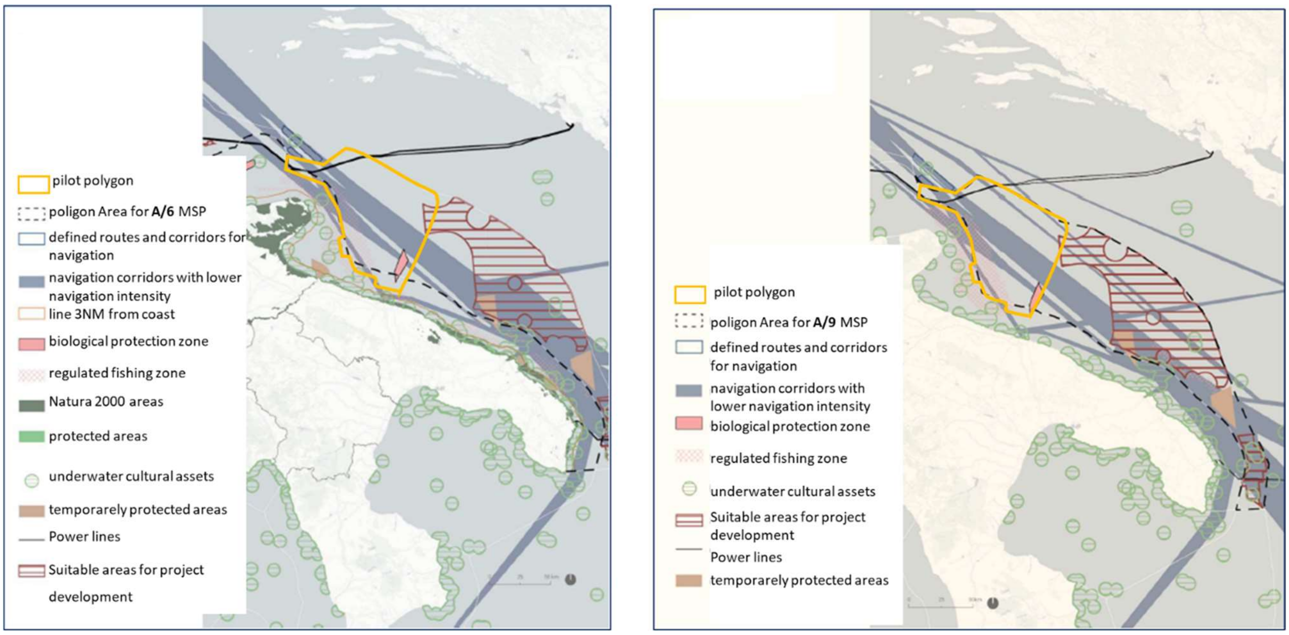

Figure 13 Approximate location of the 3 pilot polygons in the Puglia area, left figure: location of polygons in A/6; right figure: location of polygons in A/9 Source: https://www.sid.mit.gov.it/documenti-piano

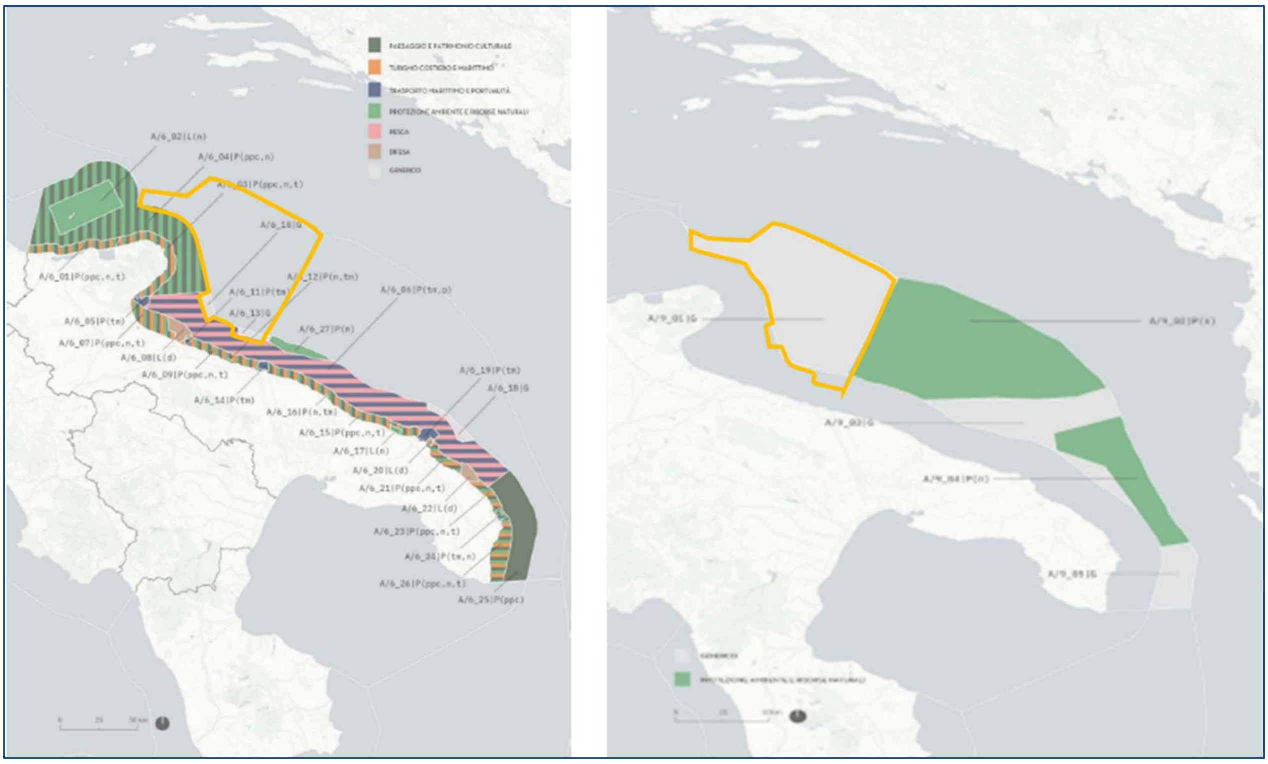

Figure 12 Description of the intended use of the respective pilot polygon (highlighted in yellow), defined in the Maritime Spatial Plan with the designation G (general), in A/6_10, A/6_13, and A/9_01 Source: https://www.sid.mit.gov.it/documenti-piano

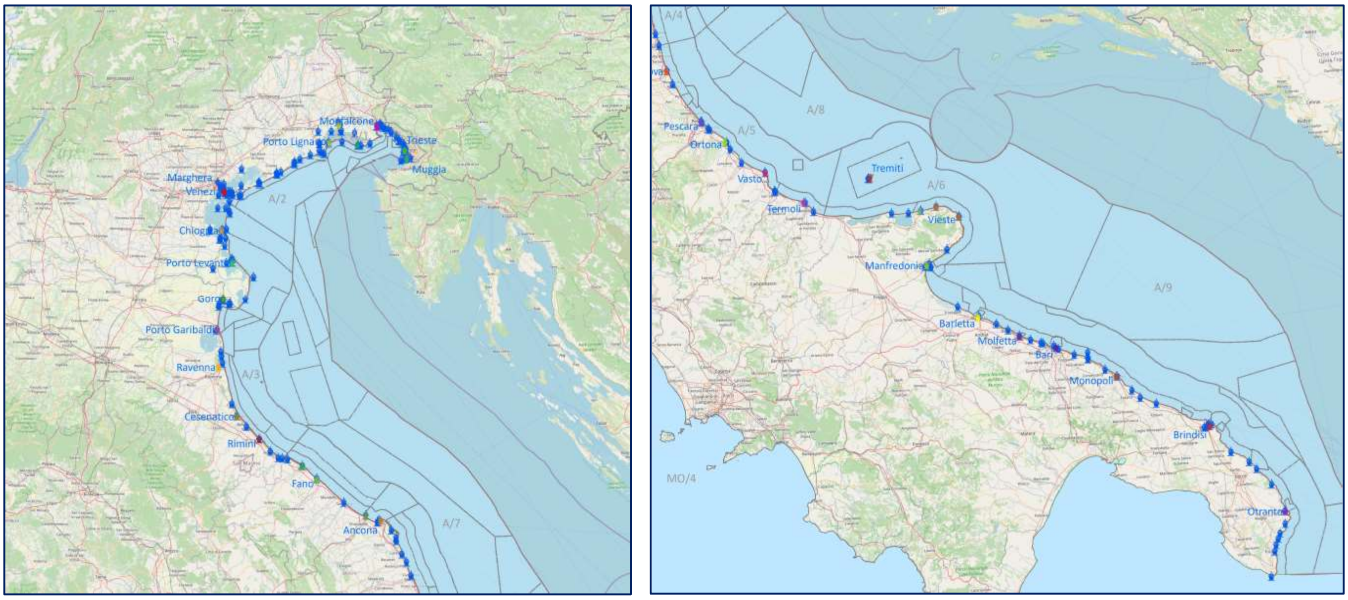

Figure 14 Distribution of ports that the pilot area infrastructure could rely on Source: https://www.sid.mit.gov.it/documenti-piano

The two northern polygons planned within the Italian sea as part of the project are in the Veneto area, with the western polygon situated entirely within the territorial waters of the Italian Republic, while the eastern polygon lies partly within the territorial waters of the Italian Republic and partly within the Exclusive Economic Zone of the Italian Republic.

According to the Italian Maritime Spatial Management Plan (*Piano di gestione dello spazio marittimo Italiano*) (https://www.sid.mit.gov.it/documenti-piano), the western polygon is located within the territorial waters of the Italian Republic, in the area designated as A/2, while the eastern one is situated in area A/7 (Figure 15). In the marine area A/2, the main uses of the sea are coastal and maritime tourism, maritime traffic and related port activities, the operation of the offshore regasification plant in Porto Viro, fisheries, aquaculture, environmental and natural resource protection, and the conservation of landscape and cultural heritage, but without specific references to energy-related developments. The western polygon located within subzone A/2 most likely entirely encompasses sub-unit A/2_05[2], which is marked with the letter G, indicating its general purpose of use. Accordingly, within the pilot polygon in this area, it may be possible to plan renewable energy production, provided that proper planning and correct positioning of onshore units are ensured (Figure 15 and Figure 16). The eastern polygon is in subzone A/7, where the main uses of the sea include maritime traffic, fisheries, environmental and natural resource protection, landscape and cultural heritage conservation, hydrocarbon exploration and exploitation, as well as activities connected to national defence. As with the southern areas mentioned earlier, for this zone the Plan specifically emphasizes the need to ensure the long-term exploitation of already existing natural gas deposits in a manner safe for human health and the environment, while reducing conflicts and increasing synergies with other

[2] for the exact position according to subunits, it is necessary to check the coordinates in the GIS system

sectors of the blue economy, in line with the guidelines and provisions of PiTESAI[3]. At the same time, it encourages experimentation and deployment, including on a large scale, of offshore renewable energy production technologies, with particular focus on wind energy. In addition, the pilot area most likely encompasses the sub-areas A/7_01 and A/7_02, designated with G (general use) and P (maritime transport) (Figure 16) (*Piano di gestione dello spazio marittimo Italiano – Area Marittima "Adriatico" Environmental Report, Strategic Environmental Assessment, Appropriate Assessment*, https://www.sid.mit.gov.it/documenti-piano). Accordingly, within this pilot polygon it is also possible to plan renewable energy production, provided that proper planning and positioning of onshore units are ensured. Both areas, in addition to the fact that the polygons are mainly located in zones marked with G (general use), are also situated in areas where the sensitivity rate of protected marine systems is the lowest[4], ranging between 0–1%, which will facilitate the permitting process and the placement of units at sea (Figure 9). At the same time, for polygon A/2, a specific instruction highlights the need to promote the development of aquaculture activities in the territorial sea, whereas such an activity is not foreseen for polygon A/7.

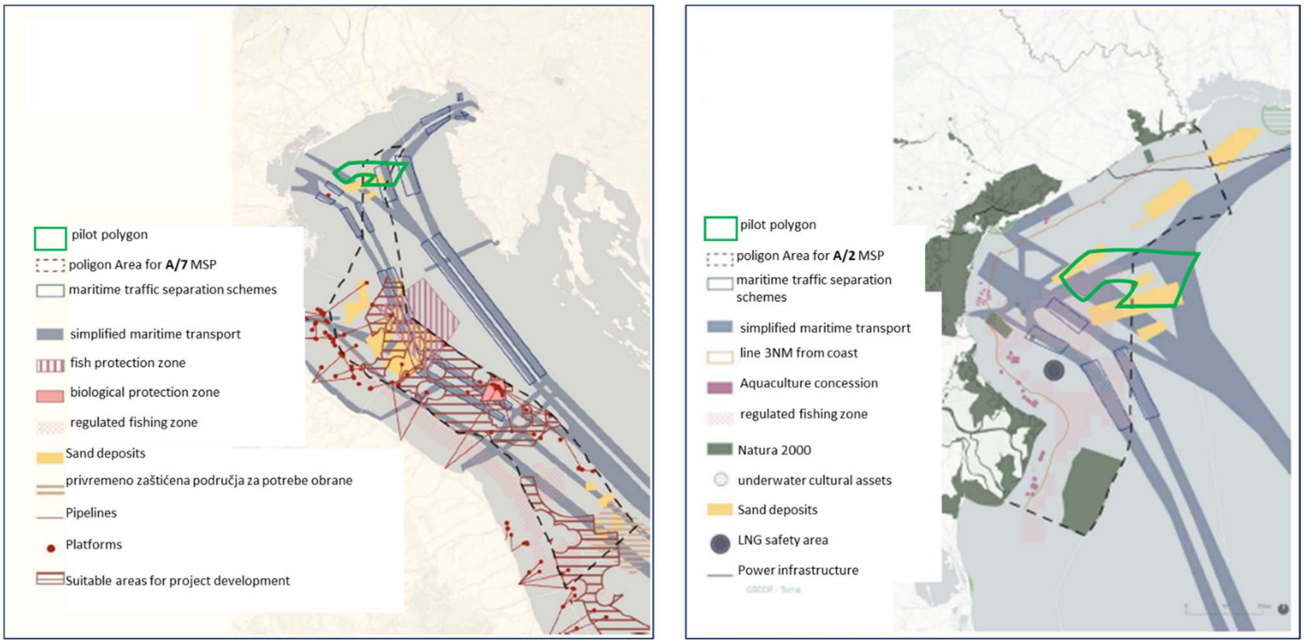

Figure 15 Approximate location of the 3 pilot polygons in the Veneto area, left figure: location of polygons in A/7; right figure: location of polygons in A/2 Source: https://www.sid.mit.gov.it/documenti-piano

[3] *PiTESAI stands for Piano per la Transizione Energetica Sostenibile delle Aree Idonee, or Plan for the Energy Transition of Sustainable Suitable Areas, and it is a plan that determines where gas and oil can still be safely and sustainably explored and exploited, and ensures that hydrocarbon exploitation is carried out only in areas where there are no significant environmental, cultural or social conflicts*

[4] *Percentage of the area covered by marine protected area systems, Natura 2000 marine ecological network areas, biological protection zones, fishing restricted areas and Fisheries Restricted Areas (FRA) in relation to the total area of sub-areas and main zones*

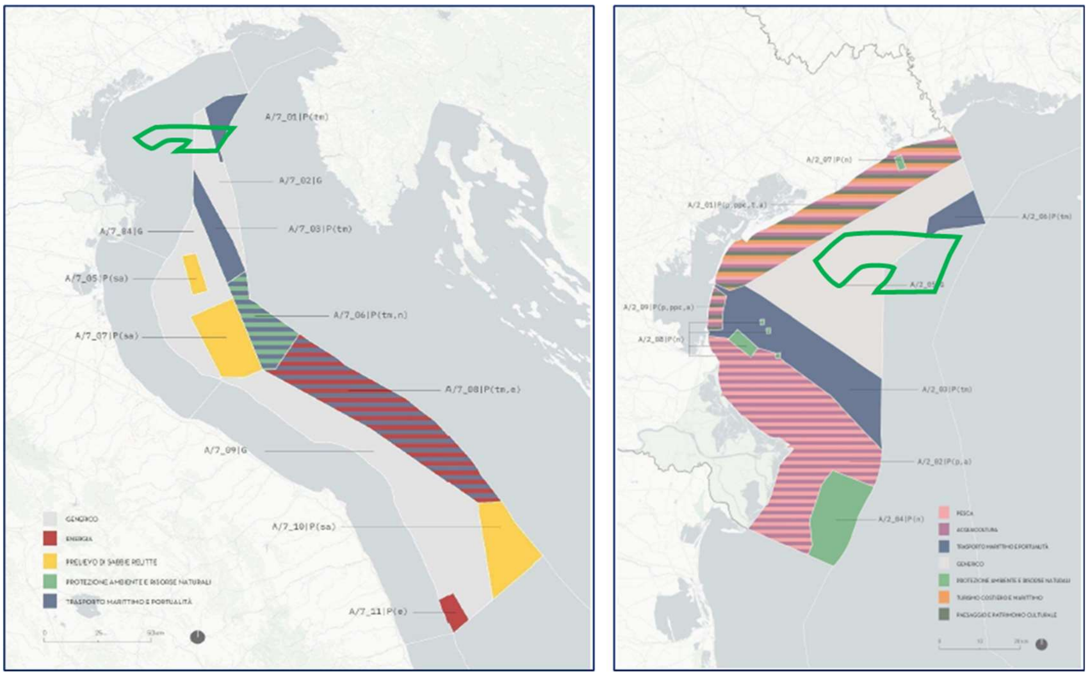

Figure 16 Description of the intended use of the respective pilot polygon (highlighted in green), defined in the Maritime Spatial Plan with the designation G (general) for A/7_02, A/2_05, and with the designation P (maritime transport) for A/7_01 Source: https://www.sid.mit.gov.it/documenti-piano

3.6. Technical Context for Offshore Wind Farms and the Blue Economy with Fixed Installations

3.6.1. Offshore Energy Source Options and Justification of Wind Potential

Production of green hydrogen requires a renewable source of electricity to supply input energy to the electrolyser system, as well as to other equipment used in the process. Several offshore energy sources are possible, such as wind, tidal, wave, and solar energy, but the most dominant source of renewable energy is offshore wind farms, followed to a lesser extent by solar panels. Although tidal and wave technologies could potentially provide renewable energy, under current technological conditions and within the Adriatic Sea environment, they are not expected to play a significant role in offshore hydrogen development.

In areas rich in wind energy resources and within marine basins, coupling wind power with seawater electrolysis has emerged as the primary method for reducing the cost of green hydrogen production, while also enabling the effective utilization of excess electricity generation. Such models of green hydrogen production are described in detail by Fang, R. (2019) (link), Li, Yi et al. (2023) (link) and Gao, X. et al. (2024) link, among others. Their research, based on financial calculations and the development of economic optimization models, confirms the role of hydrogen as a flexible energy carrier. This very function enables the efficient use of surplus electricity generated by wind farms during periods of low demand. In this way, curtailment of produced energy is reduced, and the overall utilization of renewable sources is increased. Systems that combine wind energy and hydrogen production have proven to be cost-effective and efficient approaches for integrating renewable sources into the power grid, while simultaneously enhancing economic sustainability and providing guidance for the development of pilot projects at the regional level. The financial performance indicators of wind farms, presented in these studies, further support such conclusions. The authors therefore propose integrated systems in which wind farms are coupled with green hydrogen production through electrolyzers, whereby surplus electricity is used for electrolysis. The emphasis is precisely on this surplus energy, which would otherwise remain unused, and by redirecting it into hydrogen production, the overall efficiency of the system is increased. In this model, hydrogen is conceived as a flexible energy carrier, serving as a means of storing surplus energy for later use. This ensures an optimal distribution of excess wind energy between grid supply and hydrogen production. All the referenced studies emphasize that hydrogen is a key element, as it enables long-term storage of surplus energy that cannot be immediately fed into the grid or consumed on-site. In this way, wind energy curtailment is reduced, and the overall utilization rate of renewable sources is increased. Furthermore, the energy stored in the form of hydrogen can, when needed, be used to power fuel cells, supply industrial and transport consumers, or be reintegrated into the power grid.

3.6.2.System Architectures: Offshore, Onshore, and Hybrid

Offshore wind farms can be combined with green hydrogen technologies, with production possible both onshore and offshore. There is also the option of establishing hybrid systems with solar modules, either on land or at sea. Thus, in the production of green hydrogen from renewable energy sources, various combinations of different renewables and technologies are possible within a single facility or energy network (Figure 17).

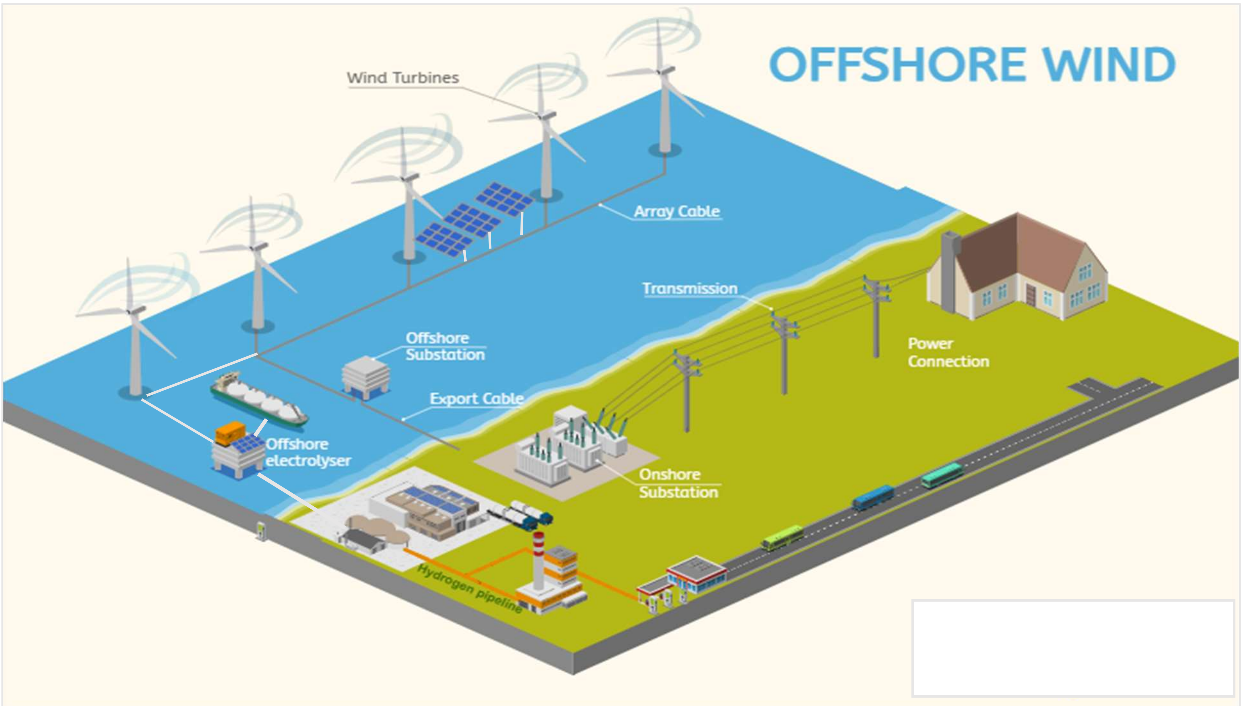

Figure 17 Overview of the of hybrid systems

Hybrid systems in the energy sector refer to the combination of different sources and technologies that ensure stable and flexible energy production. In the context of offshore renewable sources, hybrid systems involve the integration of offshore wind farms, solar panels that can be installed at sea (*floating PV*) or onshore, and electrolyzers for green hydrogen production. The electricity generated in such a system has two main uses: one part is transmitted via cables to the national or local power grid, while the other part is used for green hydrogen production in the electrolyser. The electrolyzers may be located offshore, on a specialized platform or larger barge, or onshore, within a coastal facility. In both cases, the electrolyser produces green hydrogen, which is then stored in tanks and transported through pipelines to industrial zones, or used to fuel hydrogen-powered ships and trucks in nearby ports. This enables the flexible allocation of energy depending on market needs and grid conditions, thereby achieving a more stable electricity supply, better grid utilization, and multiple options for the use of the produced energy.

Within this project, hybrid systems specifically refer to the integration of wind and solar energy with battery systems and electrolyzers into flexible energy projects, both offshore and onshore.

In addition to wind as an energy source, solar panels are increasingly appearing in combination, although the use of solar energy for hydrogen production at sea still represents a relatively new sector. Offshore solar energy production is based on the installation of floating solar panels on the sea surface or on platform structures alongside other infrastructure elements, to generate electricity, which is then immediately used on-site, without the need for additional transmission, to produce renewable hydrogen through electrolysis. These panels can be placed directly on the platform next to the electrolyser, but more commonly they are installed on floating structures positioned between wind turbines, the so-called *floating PV*, as this approach enables efficient use of available sea space and optimal integration with the wind farm.

Such solar installations and their applications are classified according to wave conditions, ranging from calm waters to areas with moderate waves, up to open sea locations where waves can reach heights of up to ten meters (Venugopalan et al., 2024). While most commercial floating solar installations today are in sheltered calm-water sites or areas with waves up to one meter, studies and pilot projects are currently being developed for open-sea conditions. Offshore solar energy was also an explicit topic in the tenders for the Hollandse Kust North (CrossWind, 2022), Hollandse Kust West (OranjeWind, 2023), and IJmuiden Ver Beta (2024) wind farms. Additionally, the companies SolarDuck and RWE recently installed the Merganser pilot project, a 0.5 MWp floating solar power plant located 12 kilometers off the Dutch coast in the North Sea, representing an important step forward in testing the technology under open-sea conditions (Venugopalan et al., 2024). Floating solar installations and their sites are categorized according to wave conditions. Floating solar modules are classified into four categories:

1. Floating solar panels on calm water
2. Floating solar modules suitable for wave heights up to 1 m
3. Floating solar modules suitable for wave heights up to 2 m (TRL 4)
4. Floating solar modules suitable for open-sea conditions (wave heights around 10 m)

Like offshore wind farms, electricity generation from offshore/platform-based solar is intermittent, but its production profile shows little correlation with that of offshore wind farms. This is precisely why these two energy sources have strong potential for complementarity, resulting in a greater number of hours per year with guaranteed positive energy export and enabling better utilization of transmission cables or electrolyzers. This can be of significant value for offshore hydrogen production, as systems can operate at minimal load, while energy storage in batteries or through innovative storage concepts can further improve the continuity of supply to offshore hydrogen production facilities.

The integration of offshore wind, solar, and green hydrogen production opens new perspectives for the energy transition, particularly in countries with favourable natural resources such as Croatia. While offshore wind represents the most mature and well-studied form of energy generation, floating/platform-based solar systems are only now entering the development phase, but they already show potential as a complement to wind farms. Since the production profiles of wind and offshore solar overlap only minimally, their combination allows for a greater number of operating hours per year with ensured generation.

Different scenarios, hydrogen production offshore or onshore, each have their specific advantages and challenges. Offshore production eliminates transmission losses, frees up coastal space, and enables the immediate use of hydrogen for maritime transport, but it is technically and safety-wise more complex and more expensive. Onshore production, on the other hand, is simpler to integrate into existing energy and logistics flows, but it requires larger amounts of water, significant coastal land areas, and incurs energy losses during transmission from offshore sites.

By combining wind, solar, battery systems, and electrolyzers, a flexible hybrid model is created that provides a more stable supply, reduces energy curtailment, and opens new value chains through the application of hydrogen in industry, transport, and energy exports. Such projects represent a crucial step toward a sustainable energy system of the future, and pilot projects and demonstration facilities already confirm that technological development is underway. In the long term, it is expected that precisely these hybrid concepts, alongside continued cost reductions and increased reliability, will become the backbone of decarbonized energy and make a significant contribution to achieving climate neutrality by 2050.

3.6.3. Process Flow

The process of generating electricity and green hydrogen, along with the associated installation and structural elements, begins with electricity production from wind turbines, which provide output power in either alternating current (AC) or direct current (DC) form, depending on the configuration. This is followed by the conversion of electricity using transformers and rectifiers, since electrolyzers operate on direct current. In the case of offshore production, seawater is the raw material for green hydrogen production and must be processed to an ultra-pure quality. Inadequate water treatment can impair operation and damage the electrolyzer; therefore, it must be filtered and purified, and then discharged, with the specific treatment solution depending on the type of electrolyzer selected. For this reason, a seawater desalination and demineralization unit is placed on the platform or barge, producing the ultra-pure water required for electrolyzer operation. Furthermore, while the electrolyzer is operating (PEM, alkaline, or SOEC), gases (O_2 and H_2) are generated at the anode and cathode, but at the same time water (i.e., the electrolyte) circulates through the cell, which means that the output of each module contains a mixture of gas and water droplets (or electrolyte). At this stage of production, gas separation takes place, which ensures that H_2 and O_2 do not come into contact with each other due to the risk of explosion, as well as to meet market requirements that demand nearly pure hydrogen (for fuel cells, a purity level of 99.999% is often expected).

Another significant reason is the residual moisture in the H_2 stream, which could cause problems during compression and storage in the form of accelerated corrosion and damage. After the separation phase, the produced hydrogen undergoes purification. Here, technologies such as membrane systems, catalytic purifiers, or PSA (Pressure Swing Adsorption) are applied to remove residual gases and impurities. The goal is to obtain high-purity hydrogen, for example at levels of 99.9% or higher, making it suitable for storage and use across different sectors.

The next step is drying, during which water vapor and electrolyte droplets are removed from the produced gas. This is most achieved using adsorption dryers (e.g., molecular sieves) or through cooling, ensuring gas stability and preventing corrosion or issues during subsequent compression. Once the hydrogen is purified and dried, the process moves to the compression stage. Hydrogen is compressed to high pressures, typically between 200 and 700 bar, to reduce its volume and enable efficient storage or transport.

Different types of compressors can be used for this purpose, with the choice of technology depending on end-user needs and the planned distribution method. Finally, the process concludes with transport and storage. Hydrogen can be transported via pipelines, tankers, or in liquefied form at -253 °C, while underground solutions, such as storage in salt caverns or depleted gas reservoirs, are also being considered for long-term storage. The choice of method depends on the quantities of hydrogen produced, the distance to consumers, and its intended use, whether for industrial processes, energy, or transport.

When hydrogen is produced onshore, the process is somewhat simpler. Electricity from the wind farm is transmitted via cable to the coast, where grid connection and conversion take place, while at the same time supplying onshore electrolyzers. Water supply in this case is less demanding, since available drinking or technical water is used, which typically does not require desalination, but only demineralization. After electrolysis in the selected type of electrolyzer, hydrogen undergoes conditioning and compression, i.e., drying and pressurization, followed by storage and distribution via pipelines, tankers, rail, or maritime transport.

Both scenarios have their advantages and limitations (Figure 18).

	Offshore Production	Onshore Production
Water	*Requires desalination and demineralization*	*Typically drinking/industrial water, only demineralization*
Electrolyzers	*Located on a platform, require additional space and safety zones*	*Onshore, simpler installation, easier maintenance*
Compression & Storage	*More complex, expensive, less flexible*	*Easier integration with pipelines and/or tankers*
Energy Export	*Export of H_2 (via pipeline or ship)*	*Export of electricity (via cable) and hydrogen*
CAPEX/OPEX	*High (platform, safety, O&M accessibility)*	*Low (utilizes existing onshore infrastructure)*
Flexibility	*Limited (depending on platform location and access)*	*High (location can be chosen close to consumers)*
Electrolyzer Type	*PEM*	*Alkaline and SOEC*

Figure 18 Differences between onshore and offshore production

3.6.3.1. Electrolyzer Technologies

As previously noted, the most used types of electrolyzers are alkaline electrolyzers, proton exchange membrane (PEM) electrolyzers, and solid oxide electrolyzers (SOEC) (Figure 19). In practice, PEM and alkaline systems still dominate today, while high costs remain the key reason for the slower adoption of solid oxide electrolyzers. According to Ghaebi Panah, P. et al. (2022), alkaline electrolyzers represent the most mature technology, being reliable for continuous and stable production in industrial onshore plants, with a proven operational lifetime of up to 100,000 hours. Their main drawback is poor adaptability to variable renewable energy sources, such as wind and solar, which makes them less suitable for offshore environments. In addition, they produce hydrogen at low pressure, requiring additional compression systems, which makes them more suitable for deployment at onshore locations near industrial users.

PEM electrolyzers (*proton exchange membrane*) offer several advantages over alkaline systems. Their development began in the 2000s, with early applications in the automotive industry. They can operate flexibly at partial loads and respond quickly to fluctuations in renewable electricity generation, which makes them particularly suitable for integration with offshore wind farms and solar panels, where production is inherently variable. Unlike alkaline electrolyzers, PEM systems produce hydrogen at high pressure, reducing the need for additional compression and facilitating the transport of hydrogen via pipelines or storage tanks from offshore to onshore. Today, PEM systems with capacities above 10 MW are already in use, making them suitable for large-scale offshore projects. Their main drawbacks are higher investment costs (CAPEX) and shorter membrane lifetimes, but further cost reductions and technological improvements are expected with large-scale deployment.

Solid oxide electrolyzers (SOEC) offer very high efficiency and can utilize heat from industrial processes, but they are still not sufficiently reliable for long-term operation. Since they operate at high temperatures of around 800 °C, they require stable conditions and continuous operation without frequent shutdowns, which significantly complicates their application offshore. For this reason, they are currently more often considered for onshore industrial applications, particularly where excess heat is available. An additional advantage is their reversibility, meaning they can also be used as fuel cells, making them a flexible solution for onshore industry.

Considering offshore conditions, PEM electrolyzers currently represent the best solution for offshore installations, while alkaline systems remain most widely used in stable onshore environments. In the long term, SOEC could play a significant role in combination with offshore wind farms, but only after further technological maturity and improvements in reliability. In conclusion, PEM electrolyzers, due to their higher technological maturity, relatively low spatial requirements and weight, better tolerance of intermittent and variable electricity supply, are more flexible than alkaline electrolyzers.

In conclusion, for onshore locations the most effective solutions remain alkaline and SOEC electrolyzers, while for offshore applications and variable renewable sources, the use of PEM technology is currently recommended.

Electrolyzer	Advantages	Disadvantages	Most Suitable Application
Alkaline Electrolyzer	*Most mature and reliable technology* *Long lifetime (up to 100,000 operating hours)* *Stable and continuous operation* *Proven industrial technology*	*Limited adaptability to variable renewable sources (wind, solar)* *Low production pressure → requires additional compression* *Less suitable for offshore environments*	*Onshore industrial plants near end-users*
PEM Electrolyzer	*Flexible operation under partial loads* *Rapid response to fluctuations in electricity supply* *Produces hydrogen at high pressure* *Compact, with lower space and weight requirements* *Suitable for large-scale projects (>10 MW)*	*Higher CAPEX* *Shorter membrane lifespan* *Technology still maturing, though costs are decreasing*	*Offshore wind and solar farms, marine environments*
SOEC (Solid Oxide Electrolyzer)	*Very high efficiency* *Can utilize waste heat from industry* *Reversible (can also operate as a fuel cell)*	*High operating temperatures (~800 °C)* *Lower reliability for long-term operation* *Poor tolerance to frequent start-ups and shutdowns* *Not suitable for variable renewable sources*	*Onshore industrial plants with excess heat; long-term potential for offshore applications once technology matures*

Figure 19 Electrolyser types and usage possibilities

3.6.3.2. Hydrogen Purification, Cooling, Compression, and Logistic

The next step in the process is conditioning, which includes purification, drying, cooling, and gas compression (https://corpapps.parker.com/interactive-media/parker-hannifin-world/hydrogen-applications/production.html). Although green hydrogen produced by an electrolyzer is of high purity, the gas still contains trace impurities that need to be removed depending on its final application. Typical impurities in the hydrogen stream include moisture (H_2O), originating from the gas–water separator, oxygen (O_2), which may "leak" through the membrane or via diffusion, and gases such as nitrogen (N_2) and CO_2 in cases where air enters the system. In alkaline systems, impurities may also result from electrolyte residues. Hydrogen purification is essential for several reasons: for safety, since removing oxygen and moisture prevents the formation of explosive mixtures and corrosion; for market requirements, as fuel cells demand extremely high purity standards, most commonly 99.999% (so-called "5N"); and for compliance with international standards that set threshold values for moisture, O_2, CO, CO_2, and sulfur compounds in the gas. The drying and purification process is carried out using membrane systems, adsorbers, desiccants, or molecular sieves. Among these methods, the literature most frequently highlights molecular sieve technology as the most common in large-scale systems (PSA – Pressure Swing Adsorption), which removes moisture, O_2, N_2, CO_2, and other impurities down to 99.999% purity (so-called "fuel cell grade"). This method is capable of continuous operation and has been proven in large industrial systems and commercial hydrogen production. However, it requires compressors and valves, which makes the system inherently more complex and expensive. Purification using membrane systems (polymeric, metallic, or electrolyte membranes) is highly effective for removing O_2, N_2, and CO_2, but system components are sensitive to moisture and require relatively stable conditions, making this method more suitable for onshore industrial facilities. Methods using adsorbers and desiccants (silica gel, zeolites, activated alumina) are most applied for removing moisture (H_2O), but they are more suitable for small- and medium-sized systems.

A review of the literature shows that ongoing research is focused on improving PSA adsorbents and developing membrane-based hydrogen purification methods, since the combination of these two methods has proven to be the most effective (Krol et al., 2024). Metallic palladium membranes and mixed metal membranes (Pd/V) are suitable for achieving hydrogen purity levels of 99.9999%. For separating natural gas–hydrogen mixtures, in which hydrogen is not the dominant component, mixed polymer membranes are often tested and applied. Therefore, in offshore systems, a well-developed and proven PSA system is expected, with the potential for additional use of membrane methods, as also noted in the available literature (Venugopalan et al., 2024).

The cooling process is essential because, during green hydrogen production, whether through alkaline electrolysis or proton exchange membrane (PEM) electrolysis, heat is released. Cooling therefore prevents boiling and evaporation of the electrolyte solution, which could compromise safety and reduce the efficiency of the reaction. In addition, in later stages of the process, hydrogen must be compressed, and this step also requires additional cooling.

After production, hydrogen must be conditioned for practical storage and distribution. This is achieved either by compression or liquefaction. Since hydrogen is typically produced at relatively low pressures (20–40 bar), it must be compressed before transport using compressors, with volumetric and centrifugal compressors being the most common today. Although volumetric compressors (particularly diaphragm and piston types) are the most widely used in today's hydrogen industry, since they enable the high pressures required for filling storage tanks and for transport in cylinders or tankers, for offshore applications the recommended approach is a combination: centrifugal compressors are used for large volumes and stable hydrogen flows delivered via pipelines to shore at medium pressure, while volumetric compressors (diaphragm/piston) are applied for high-pressure storage or for filling ships/tankers directly on the platform, in situ. In cases where large-scale transport is required but pipelines are not available, hydrogen is typically transported and delivered in liquid form, produced through liquefaction. Gaseous hydrogen is liquefied by cooling it to below –253 °C and can then be stored in liquefaction facilities in large, insulated tanks. One of the advantages of hydrogen is that it allows long-term storage of renewable energy in significant quantities.

In terms of transport, hydrogen has the major advantage of being easily transported over long distances, and in line with this, a hydrogen pipeline network is planned across Europe. Efficient infrastructure is also one of the key prerequisites for the use of hydrogen (EU strategies). Therefore, the core H_2 network is a key component of the future EU hydrogen infrastructure, connecting hydrogen import and storage points with major industrial centres and power plants, thus forming the backbone for the comprehensive expansion of the network. According to forecasts by both regulatory authorities and industry representatives, part of the core H_2 network will consist of repurposed natural gas pipelines, complemented by newly built hydrogen pipelines. The use of existing pipelines (including existing onshore connection points) is more economically viable, has a lower environmental impact, and is expected to benefit from shorter permitting procedures. The possibility of repurposing existing pipelines for hydrogen transport has proven to be the main tool for rapidly and cost-effectively developing hydrogen infrastructure, as conversion is 60–70% cheaper than building new pipelines (https://www.h2ercules.com/en, Hrvatski Integrirani Nacionalni Energetski i Klimatski Plan rev. 2025, Hrvatska Strategija za vodik 2021-2050, EU Hydrogen Strategy, A Hydrogen Strategy for a Climate-Neutral Europe).

Of course, in cases where hydrogen is produced at locations far from transmission pipelines, the construction of new pipelines is foreseen. The advantage of a new pipeline is that its design can be tailored to the planned production capacities from platforms in the area, both in terms of materials and diameter as well as the routing.

An alternative option for transporting hydrogen through pipelines is blending it with natural gas. However, in such cases, the market value of green hydrogen decreases, as within the mixture hydrogen is valued based on its calorific value, which is approximately one-third of the calorific value of a cubic meter of natural gas. In this case, the only additional value that can be attributed to the hydrogen is from its green origin certification.

The reason this technology is considered feasible in the near future is the fact that a dedicated hydrogen transport network has not yet been established, and in the meantime, such an approach provides a way to deliver hydrogen from producers to end-users. Once blended, there are two options: direct sale of the hydrogen–natural gas mixture or extraction of hydrogen from the natural gas stream.

Hydrogen produced offshore can also be transported by sea, which is expected in very deep waters or over long distances. According to Dukku, H.B. et al., 2025, transporting hydrogen via pipelines is economically viable for distances up to around 1,500 km. By ship, hydrogen can be transported in gaseous or liquid form, or in carriers such as ammonia (NH_3), liquid organic hydrogen carriers (LOHC), or methanol (Figure 20).

Criterion	Pipelines (onshore/offshore)	Ships (gas, LH_2, NH_3, MeOH)
Application	*Continuous transport of large volumes between production and consumption centers*	*Flexible transport over long distances and to locations without pipelines*
Capacity	*Very high capacity (GW scale, thousands of km)*	*Limited per ship, depends on form (gas, LH_2, NH_3)*
Energy losses	*Low (1–5% during transmission)*	*High for LH_2 (30–36% liquefaction + boil-off), medium for NH_3 (10–20% synthesis/deconversion)*
Infrastructure	*Existing gas network can be repurposed (EHB, Plinacro, SNAM)*	*Specialized ships and terminals required; NH_3/MeOH already have global logistics*
Environmental impact	*Low, but requires land and coastal space; safety zones needed*	*Smaller spatial impact; risks of LH_2 leakage or NH3 toxicity*
Flexibility	*Fixed route, high reliability and safety*	*High flexibility (global trade), but more complex logistics*
Maturity level	*Mature technology; EHB plans >60% of the network through conversion of existing pipelines*	*Liquid H_2 in pilot phase; NH_3 fully commercial; compressed H_2 limited*
Distance threshold	*More favorable for ≤1500 km*	*More favorable for >1500–2000 km (global trade, intercontinental transport)*

Figure 20 Hydrogen transport comparison: pipelines vs. ships

3.6.3.3. Hydrogen storage

Hydrogen storage is a key technology that enables the advancement of hydrogen and fuel cell applications in areas such as stationary power, portable energy, and transportation. Hydrogen has the highest energy per unit mass of all fuels; however, its low density at room temperature results in a low amount of energy per unit volume, which makes it necessary to further develop advanced storage methods with higher energy density potential. The hydrogen storage phase is essential for managing fluctuations in supply and demand and represents a critical link in the production, distribution, and consumption chain, as it allows balancing between the intermittent nature of renewable energy production and variable demand. Hydrogen storage can take the form of compressed gas, cryogenic liquid, or solid-state storage through absorption or adsorption. While compressed gas requires high-pressure tanks and liquid storage requires extremely low temperatures, solid-state methods use materials such as metal hydrides or carbon aerogels that chemically or physically bind hydrogen (Figure 21). Newer methods include liquid organic hydrogen carriers (LOHC), which offer easier handling and transport at ambient temperature.

As for storage locations, in addition to cryogenic or pressurized tanks, hydrogen can also be stored in depleted oil and gas reservoirs, salt caverns, or aquifers, particularly for large-scale storage needs.

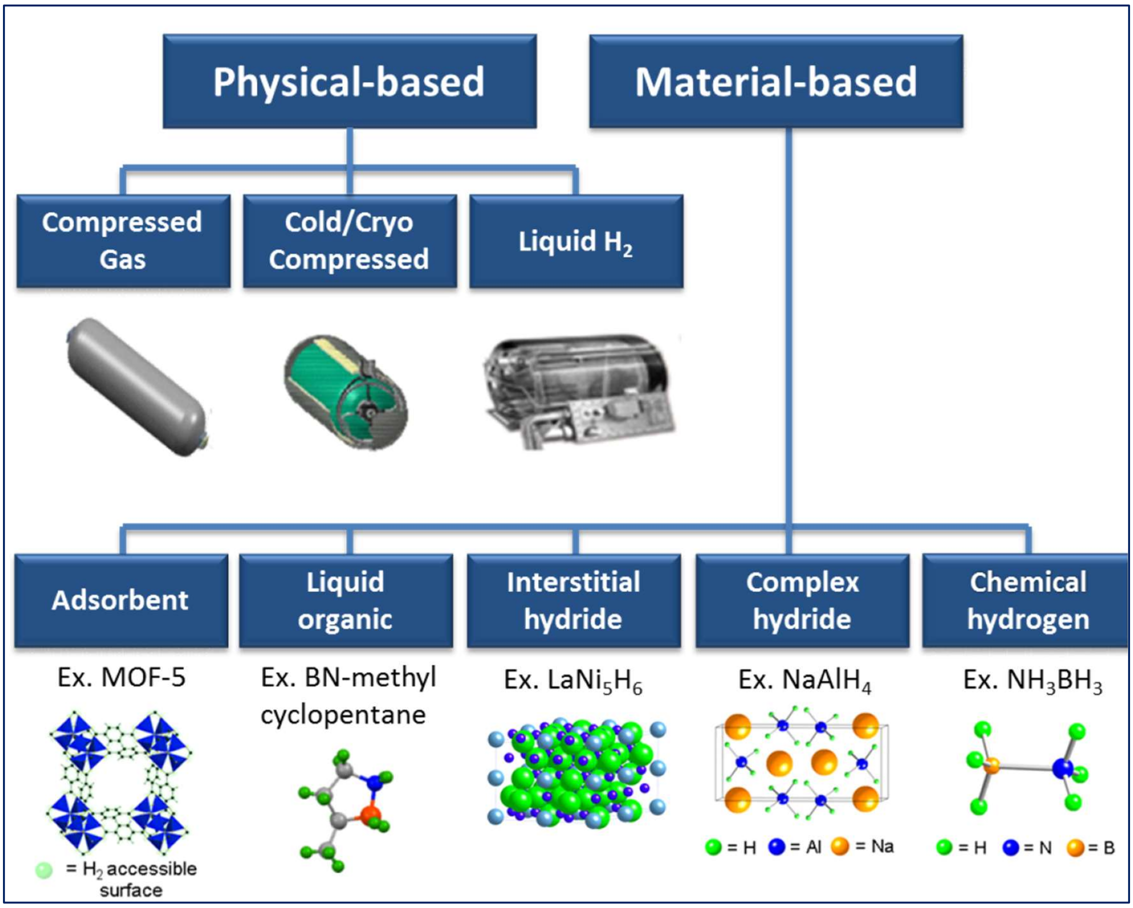

Figure 21 ***Methods of Hydrogen Storage*** *Source: https://www.energy.gov/eere/fuelcells/hydrogen-storage*

Compressed hydrogen gas is stored in high-pressure tanks, typically made from materials such as steel, aluminum, or composite materials. This method is suitable for industrial applications and stationary energy storage but requires very high storage pressures (350–700 bar) (https://www.energy.gov/eere/fuelcells/hydrogen-storage). It is the most widespread method for hydrogen transport and refuelling of hydrogen-powered vehicles. The main advantage of this storage method is its technological maturity and the wide availability of solutions, while its main drawback lies in the limited storage capacity and the high energy consumption required for compression.

This method is also often used for transport, although it is energy intensive. In its liquefied form (LH_2), hydrogen is cooled to cryogenic temperatures of up to −253 °C to reach a liquid state, which significantly reduces its volume compared to the gaseous form and thereby increases its density, allowing larger quantities to be stored in smaller volumes. The advantage of liquefied hydrogen is its suitability for long-distance transport and large-scale storage, while the main drawbacks are the high energy cost of cooling, amounting to 30–40% of the energy content of hydrogen, and the need for storage in specialized, insulated tanks to prevent evaporation. Such cryogenic tanks feature multilayer insulation and a vacuum, operating at pressures typically near atmospheric (1–10 bar) and temperatures around −253 °C (close to absolute zero). Their main purpose is to maintain low temperatures and prevent evaporation (known as *boil-off*). In contrast, compressed hydrogen in high-pressure vessels is stored at ambient temperature but under pressures of 350 to 700 bar, with tanks made of steel or composite materials. The primary goal of these tanks is to withstand high pressure and ensure sufficiently dense storage. There are also newer and more innovative methods, such as solid-state storage, in which hydrogen is stored within or on the surface of solid materials. One approach is absorption, where hydrogen chemically bonds with a material, such as metals, forming metal hydrides. Another is adsorption, where hydrogen molecules physically adhere to the surface of porous materials such as carbon aerogels or graphene. In addition, there is chemical storage (e.g., LOHC – Liquid Organic Hydrogen Carriers), in which liquid organic carriers are organic molecules that chemically absorb hydrogen under high pressure and release it under low pressure through a reversible process. This method offers advantages in handling and transport at ambient temperature, with the potential to utilize existing fuel infrastructure.

The main advantages of these innovative storage technologies are their high storage density and safer handling. However, their key limitation lies in the fact that these methods are not yet widely commercialized and require additional energy to release hydrogen from the compounds. Therefore, when hydrogen is produced on offshore wind farms or other marine facilities, storage can be achieved in several ways depending on the distance from the shore and the planned consumption.

In the storage process, one of the key factors influencing the overall efficiency of the entire energy cycle is the amount of energy required to prepare hydrogen for storage. The compression process itself requires additional energy consumption, typically between 10 and 15% of the energy contained in the hydrogen, while for liquefaction this share is even higher, reaching 30 to 40%. Similarly, in solid-state storage systems, such as metal hydrides or liquid organic carriers, energy is needed not only for storage but also for the subsequent release of hydrogen, which further reduces the overall system efficiency. Given that hydrogen will primarily be produced from offshore renewable sources, in the early development phases in Italy and Croatia it is most realistic to expect storage in the form of compressed gas in modular tanks, rather than liquefied hydrogen. This is because the compression process results in lower energy losses compared to liquefaction, which would significantly reduce the overall system efficiency in pilot areas. For larger facilities and more mature stages of project development, hydrogen can be liquefied and stored in cryogenic tanks at sea or on LNG-type vessels. However, due to the high energy costs of liquefaction, it is more commonly considered to transport raw compressed gas to the coast, where liquefaction would take place within an industrial coastal zone (brownfield investments). In later, more advanced stages of green hydrogen production development, it would be advisable to consider large-scale and long-term storage in underground facilities, such as depleted gas fields in the Adriatic. In addition to specialized above-ground tanks, hydrogen can also be stored in underground structures such as salt caverns, depleted gas fields, or aquifers, which enable the storage of very large quantities, often on a seasonal basis. This technology is already in use or under testing in Germany, the United Kingdom, and the United States. Both Italy and Croatia have offshore gas fields, and several of these are either depleted or nearing the end of their production life, making them suitable for conversion into hydrogen storage sites. The Veneto region and the Istrian County are in particularly favourable positions due to their proximity to gas fields, while hydrogen produced in the pilot areas of the Puglia region and Split-Dalmatia County would most likely be transported to shore and stored on land. Spatial requirements also present a challenge because, although hydrogen has the highest energy content per unit of mass among all fuels, its low density remains an issue even after compression or liquefaction. Consequently, storing significant amounts of energy requires large-volume tanks or heavy composite vessels. In practice, this means that hydrogen occupies more space and requires more complex logistics than fossil fuels such as gasoline or diesel, which have several times higher energy density per liter. Ports usually have limited space available for large storage tanks, and the challenge is even greater offshore, where available space on platforms is restricted. This means that, in the short term, hydrogen will need to be transported to the mainland and stored in coastal industrial zones, making underground storage or depleted gas fields the most suitable long-term solutions.

The various storage methods also differ in terms of storage duration. For example, in conventional pressurized tanks (onshore or on ships), hydrogen can be stored for days to weeks; in underground structures, storage can last for several months; while in the case of liquefied hydrogen, losses due to evaporation (so-called *boil-off*) may occur after only a few days if the tanks are not well insulated.

3.6.4. System Configuration Modalities for Green Hydrogen Production

Several concepts are currently being considered for the installation of green hydrogen production systems at sea, with the most common configurations being:

A. Offshore Electrolyzer

1. The decentralized system is characterized by electrolyzers located within or around the foundation/body/monopile structure of each wind turbine. The produced hydrogen is then transported through pipelines connecting groups of turbines. At a hub (or manifold), the H_2 is collected and compressed, after which it is transported via pipeline to the shore (Figure 22).

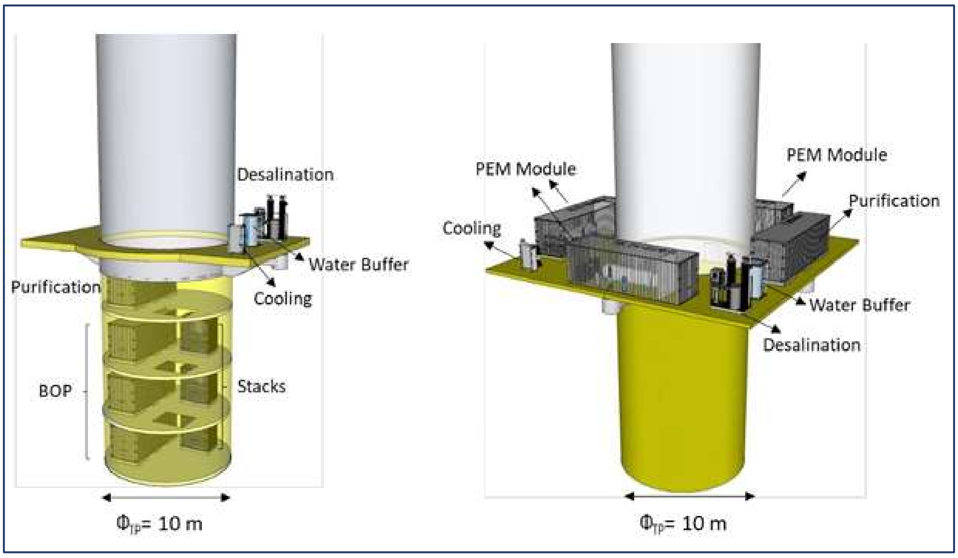

Figure 22 Concepts of turbine–electrolyzer integration for a 15 MW system: (left) within the transition piece (TP); (right) on an enlarged TP platform showing PEM modules.
Source: Chico Moreno, F. D. (2021). Design of an Electrolyzer Integrated in an Offshore Wind Turbine System. [EngD Thesis, University of Twente]. University of Twente.

2. Centralized production, where hydrogen is produced on a single platform, barge, or artificial energy island that houses all components of the H_2 system, and where electricity generated by a cluster of wind turbines and other energy sources is delivered. In this system, electrolysis takes place on the platform using desalinated seawater.

Offshore hydrogen production platforms currently under consideration can accommodate electrolyzer capacities ranging from 100 to 700 megawatts (MW), though most study examples focus on approximately 100 MW, which is considered the minimum capacity for economically viable hydrogen production using offshore platforms (Venugopalan et al., 2024). Platforms hosting electrolyzers may be newly constructed or repurposed existing structures; however, for large, centralized offshore electrolyzers, new platform construction is expected, while smaller pilot projects can be implemented on existing platforms to reduce costs. Similar to the platform concept, the *energy island* approach operates on a much larger scale and is suitable for extensive offshore wind farms with subsequent hydrogen production capacities of 1 GW or more. In addition, the scale of these systems is such that PEM technology is not necessarily the only option for electrolysis; a combination of PEM and alkaline technologies can also be applied. Currently, the Danish government, in cooperation with CIP P/S, is developing a project to connect an energy island with offshore wind farms of a total capacity of around 10 GW, with the goal of producing approximately 1 million tonnes of hydrogen per year and transporting that hydrogen via pipelines to Northern Europe (Venugopalan et al., 2024).

An additional offshore option includes FPSO and FLNG technologies, which have been developed and matured over the past decades; however, current facilities are still limited to fossil fuel resources. FPSO, or Floating Production, Storage and Offloading unit, is a large vessel or barge that serves as a mobile facility where fluid is produced, stored, and then transferred to tankers or pipelines. For hydrogen production purposes, this concept is referred to as a Floating Hydrogen Production unit (sometimes called $FPSOH_2$), which follows the same principle: electrolyzers and auxiliary systems are installed on a vessel or barge, where hydrogen is produced, stored, and shipped. However, a dedicated FPSO concept for hydrogen production from renewable energy sources has not yet been developed.

Although individual FPSO components for hydrogen production are at a relatively high level of technological readiness, their integration into a complete production system still presents a challenge. In FPSO facilities, it is essential to combine the system with a **Floating Liquid Hydrogen (FLH$_2$)** unit — a specialized vessel or barge designed to liquefy hydrogen at sea and transport it directly, without the need for coastal infrastructure. However, this system is still in its early stages of development.

B. Onshore Electrolyzer

1.Direct transmission of electricity from offshore to onshore

In this case, the electrical energy produced by the offshore wind farm is transmitted via cables to the shore, where it is converted and connected to the power grid while simultaneously supplying onshore electrolyzers. The system is simpler to implement, as it relies on existing infrastructure and coastal power connections. Water supply for electrolysis is also easier to manage than offshore, since potable or technical water available in coastal areas is typically used, which generally does not require desalination, only demineralization. However, the increased water demand could pose an environmental concern. After electrolysis in one of the selected types of electrolyzers (PEM, alkaline, or SOEC), the process continues with hydrogen conditioning and compression, followed by storage and transport via pipelines, tankers, rail, or maritime shipping.

2.Centralized Coastal Energy Hub

In this scenario, electrical energy from offshore wind farms, as well as from other renewable sources (e.g., solar power plants, which in this case may be located onshore), is transmitted via cables to an energy hub solely for hydrocarbon production. These hubs host large electrolyzer capacities, together with infrastructure for hydrogen compression, storage, and distribution.

Such hubs can be built near industrial zones, ports, or transport nodes, which facilitates the integration of produced hydrogen into local and international supply chains. The advantage of this approach lies in the easier integration into existing logistical and energy systems, while the main challenges include the high demand for water, the need for large coastal areas, and energy losses during transmission from offshore sites.

In conclusion, unlike offshore concepts where electrolysis takes place on platforms, barges, or energy islands, the onshore electrolyzer concept offers simpler operational implementation, lower maintenance costs, and reduced exposure to technical and safety risks. However, this approach also has certain limitations, it requires significant coastal space, large quantities of water for electrolysis, and additional investments in strengthening grid and logistical infrastructure (Figure 23).

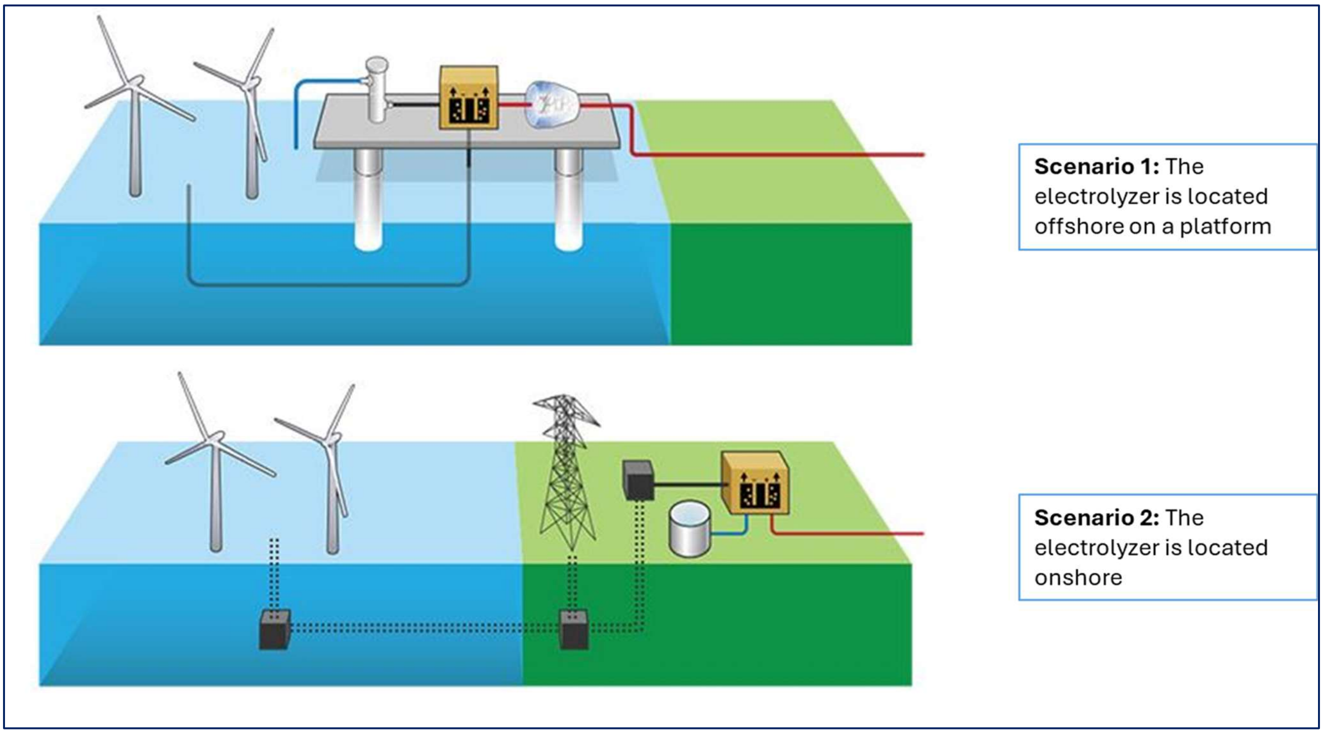

Figure 23 Layout of electrolyzers offshore (Scenario 1) and onshore (Scenario 2).
Source: https://www.nrel.gov/news/detail/program/2024/offshore-wind-turbines-offer-path-for-clean-hydrogen-production

C. Combination with Solar Modules

The development of hybrid offshore energy systems increasingly involves the combination of offshore wind farms and floating solar power plants. While wind energy is currently the dominant technology in the marine environment, offshore solar energy represents a complementary source with growing potential. Since wind and solar generation profiles overlap only slightly, their combination enables a more stable and continuous electricity supply throughout the year. This synergy increases the utilization rate of transmission infrastructure and electrolyzers, reduces the need for frequent shutdowns, and contributes to more efficient green hydrogen production. The analysis of the optimal wind-to-solar ratio at sea is crucial for planning future hybrid projects and energy islands. When designing hybrid offshore systems, different scenarios of wind–solar combinations should be considered. In configurations where most of the energy is produced from wind and a smaller share from floating solar panels, the solar component primarily serves to stabilize supply and increase the number of hours with positive generation, typically accounting for 10–20% of the total capacity. There are also scenarios in which the share of solar energy is higher, around 30 to 40%, which can be particularly useful in areas with pronounced seasonal variations in wind intensity. Floating solar (floating PV) can be installed between wind turbines, making optimal use of the sea surface, while smaller capacities can also be placed directly on platforms alongside the electrolyzer to provide immediate power for hydrogen production (Figure 17). Additionally, a portion of the solar capacity can be planned onshore, within coastal areas near energy hubs, thereby providing additional system flexibility and reducing dependence on weather conditions at sea. By carefully balancing different ratios and spatial configurations of solar installations, an optimal balance can be achieved between supply reliability, grid efficiency, and investment cost-effectiveness.

When considering the ratios of wind and solar energy in offshore hybrid systems, three approaches are possible.

In the first scenario, wind is the dominant energy source, accounting for more than 80% of the total capacity, while solar contributes only 10–20%. This approach is typical for areas with high wind energy potential, where solar serves as a complementary source that smooths production fluctuations and increases the number of hours with stable power supply.

The second scenario envisions a more balanced ratio, for example, around 60% wind and 30–40% solar. This combination is particularly suitable for regions where the seasonal or daily profiles of wind and solar complement each other, resulting in higher overall utilization of the grid and electrolyzers. In this model, floating solar panels can be installed between wind turbines or on sea surfaces unsuitable for turbine installation, while part of the capacity may also be installed onshore within coastal energy hubs.

The **third scenario** involves solar installations primarily located onshore, while offshore wind remains the main source of energy production. This approach can be advantageous in cases where coastal infrastructure is already developed, where sufficient space is available for installing solar power plants, or where the aim is to reduce the complexity of offshore installations. The main advantage lies in easier integration with existing energy hubs and industrial consumers, while still benefiting from the complementary generation profiles of wind and solar (Figure 24).

	Wind–Solar Ratio	Solar Location	Advantages	Limitations
Wind-dominant	*≥80 % wind, 10–20 % solar*	*Floating PV between turbines or on platforms near the electrolyzer*	*Simple design, stable power supply, increased hours of positive generation*	*Limited solar contribution, higher dependence on the wind profile*
Balanced system	*60 % wind, 30–40 % solar*	*Floating PV between turbines, offshore outside the wind farm + partial onshore installation*	*Better complementarity of generation profiles, higher utilization of the grid and electrolyzers, more stable production*	*Greater system complexity, higher CAPEX due to multiple locations*
Onshore solar	*predominantly wind, solar 20–30 % on-shore*	*Coastal solar plants in energy hubs*	*Easier integration into existing infrastructure, simpler maintenance, reduced offshore complexity*	*Requires coastal space, lower synergy with offshore wind farms, energy losses during transmission from sea*

Figure 24 Three different scenarios in wind and solar usage at the sea area

A comparison of these scenarios shows that the wind–solar ratio, as well as the choice of their respective locations, directly affects supply stability, grid efficiency, and economic sustainability. While offshore wind remains the primary driver of production, the inclusion of solar, whether on floating structures or onshore, provides greater flexibility and improves the overall system utilization. For the pilot areas covered by this project, when determining the optimal wind–solar ratio, wind persistence measurements should first be conducted, and based on these data, the appropriate share and placement of solar panels can then be calculated.

3.7. Multi-use with Aquaculture

The development of offshore wind farms opens new opportunities for integrating multiple maritime activities within the same area, with one of the most promising synergies being the combination of renewable energy production and aquaculture. This integration enables more efficient use of marine resources and space. Installing systems for fish, algae, or shellfish cultivation in the immediate vicinity of wind turbines can contribute to diversifying the local economy, increasing sustainability, and reducing spatial pressure on coastal areas. This approach emphasizes the multi-use concept, in which energy production and aquaculture are viewed as complementary activities, thereby adding value to existing infrastructure investments.

On the other hand, challenges include the need for a clearer regulatory framework, adaptation of technical solutions, protection of the environment and biodiversity, and coordination among various stakeholders. Timely addressing and effectively managing these challenges could significantly contribute to the development of innovative and sustainable blue economy models and their practical implementation.

In fish farming, several cage design options are possible: a) Floating flexible cages consist of a flexible floating frame, fish net enclosures, and anchoring systems; b) Floating rigid cages have a solid outer structure that stabilizes the fish enclosure and withstands large waves and marine currents. They provide a safe and stable working platform and allow the integration of automated feeding and harvesting systems; c) Semi-submersible flexible cages are designed with a flexible fish enclosure secured by a tensioned mooring system, allowing the cage to naturally submerge during storms and avoid high-energy surface zones. They are made of lightweight and low-cost materials, easy to install, and typically consist of an outer rigid frame and an adjustable ballast tank that raises or lowers the system to maintain sufficient cage volume; d) Submerged cages consist of closed flexible or rigid structures designed to remain below the surface and be raised periodically for maintenance. They feature an adjustable mooring system, can be remotely operated, and require physical access only when necessary. Their main advantage lies in avoiding wave impact (Figure 25) (Miranda et al., 2025). Fish can also be farmed in fixed-bottom cages, consisting of enclosed net structures attached to a system of piles. In recent years, such farms have gained increasing attention—particularly in China, where several fixed-bottom platforms have been installed. The main advantage of this structure is its high resistance to waves and marine currents, ensuring a stable and safe working platform that allows for the integration of automated feeding and harvesting systems. In addition to cages, fish can also be farmed in closed tanks, where the water inside the tank can be regularly recirculated and purified. The advantages of this method include precise control of water quality and protection from external threats such as algal blooms and pathogenic organisms. However, these systems are highly sensitive and require continuous monitoring, which can be difficult to implement at remote offshore locations.

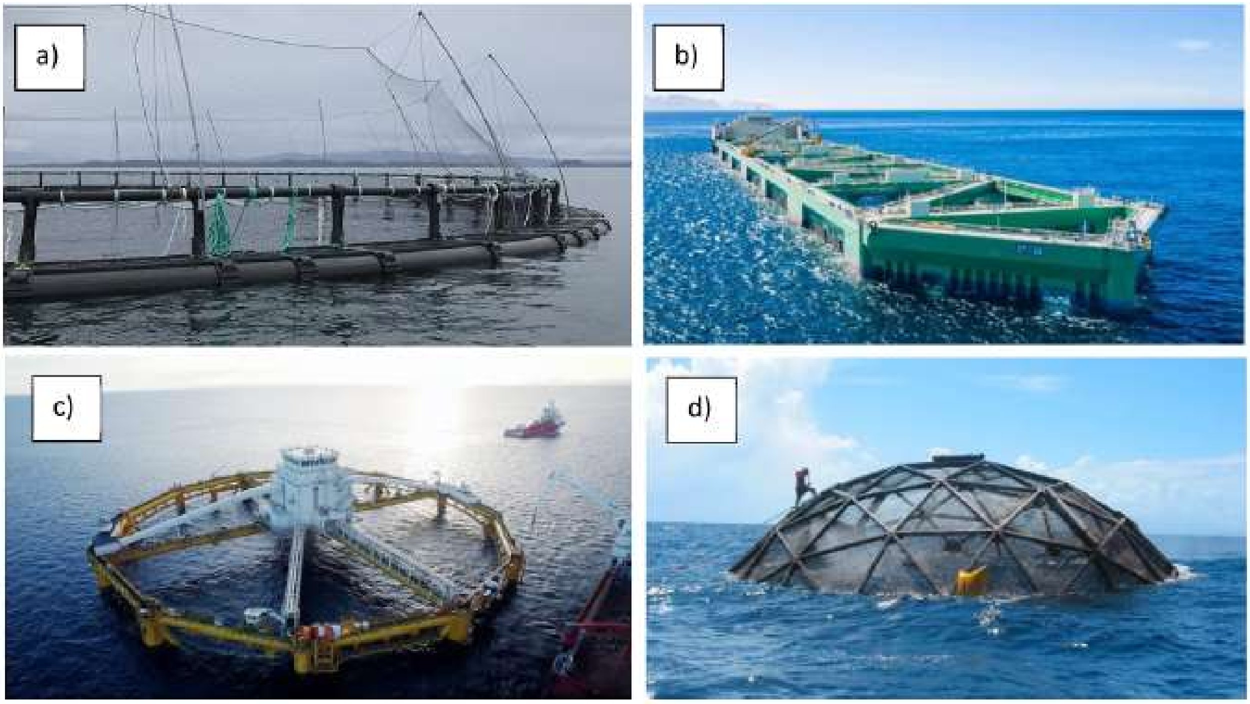

Figure 25 Possible fish-farming structures within a wind farm area: a) floating flexible cages, b) floating rigid cages, c) semi-submersible flexible cage, and d) submerged cages. Source: Miranda, F. et al., 2025. https://www.sciencedirect.com/science/article/pii/S0029801824034991?via%3Dihub

In the context of co-location with offshore wind farms, increasing attention is being given to the cultivation of LTA species (low-trophic aquaculture), species that occupy a low position in the food chain and require little or no additional feed, as they naturally feed on nutrients available in the marine environment. Examples include shellfish, seaweeds, sea cucumbers, and sea urchins. Their cultivation requires no additional inputs such as feed or fertilizers, as they rely on naturally available nutrients and phytoplankton from seawater. Consequently, their ecological footprint is significantly smaller compared to intensive aquaculture systems (e.g., salmon farming). The advantage of LTA species also lies in their contribution to mitigating eutrophication, shellfish filter the water, removing nitrogen and phosphorus, while algae absorb inorganic carbon and nutrients. In addition, these species can contribute to food security, as they are rich in proteins, minerals, and vitamins, and their production can be easily integrated into existing wind farm structures. Seaweeds, for instance, can be cultivated using long-line systems consisting of ropes anchored to the seabed and supported by buoys (Figure 26). The algae are attached to hanging lines or directly to the main ropes. This system is simple, cost-effective, and produces a highly sought-after product that also provides environmental benefits. The added value of seaweed cultivation lies in its ability to remove inorganic carbon, nitrogen, and phosphorus from seawater, making it particularly suitable for areas affected by eutrophication caused by pollution and agricultural runoff (Miranda et al., 2025). Seaweeds are cultivated for a variety of applications, for human consumption, animal feed, and to produce biomaterials such as bioplastics, biotextiles, and biocomposites (construction materials combining natural fibers and bio-resins), as they provide polymers and fibers suitable for industrial use. The global demand for seaweed is already very high and is expected to continue increasing in the coming years. Their cultivation requires no land, fresh water, or fertilizers, and increased seaweed consumption can make a significant contribution to mitigating climate change. An additional value of seaweed cultivation lies in its ability to remove inorganic carbon, nitrogen, and phosphorus from seawater, making it particularly suitable for areas affected by eutrophication caused by pollution and agricultural runoff (Miranda et al., 2025). The added value of seaweed cultivation lies in its ability to remove inorganic carbon, nitrogen, and phosphorus from seawater, making it particularly suitable for areas affected by eutrophication caused by pollution and agricultural runoff (Miranda et al., 2025). Seaweeds are cultivated for a variety of applications, for human consumption, animal feed, and to produce biomaterials such as bioplastics, biotextiles, and biocomposites (construction materials combining natural fibers and bio-resins), as they provide polymers and fibers suitable for industrial use. The global demand for seaweed is already very high and is expected to continue increasing in the coming years. Their cultivation requires no land, fresh water, or fertilizers, and increased seaweed consumption can make a significant contribution to mitigating climate change.

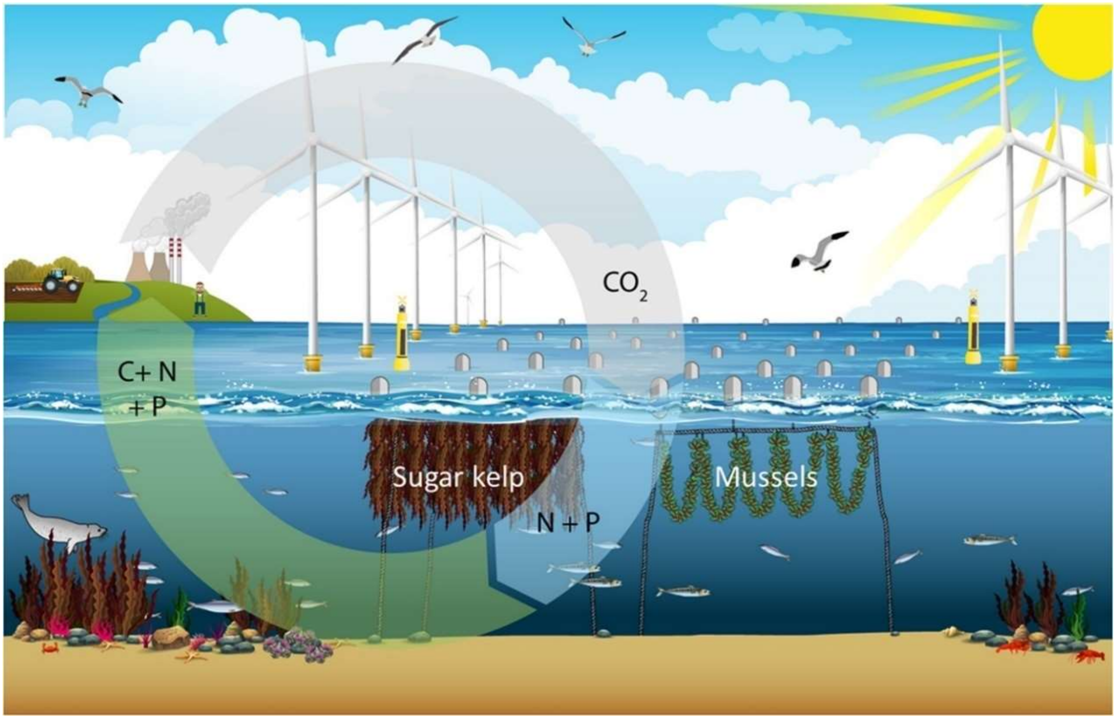

Figure 26 Multi-use application in offshore wind farms with blue mussel and sugar kelp cultivation can provide zero-emission energy, nutritious seafood, and positive ecosystem services through the capture and utilization of emissions (CO_2 and nutrients). Source: Maar, M. et al., 2023. https://www.nature.com/articles/s43247-023-01116-6

According to the analysis by Maar, M. et al. (2025), feasibility studies conducted in Northern Europe indicate that combining offshore wind farms with the cultivation of mussels (*Mytilus spp.*) and kelp seaweed is a promising approach, particularly in the North Sea due to its salinity. Furthermore, in areas with excess nutrients (eutrophic zones), shellfish farming can serve as a mitigation practice, as mussels filter and remove nitrogen and phosphorus from seawater. In such cases, mussels tend to be smaller and more variable in size, making them less suitable for consumption but still beneficial for improving marine water quality. A similar situation, characterized by nutrient surpluses, occasionally occurs in the northern Adriatic Sea, where shellfish farming could help restore ecological balance.

3.8. Existing Projects — Multi-Use Projects with Aquaculture and Studies

Since offshore hydrogen production is a relatively new field, with rapidly increasing interest in recent years, practical experience with offshore hydrogen remains limited. To date, only a few demonstration projects have been launched to assess feasibility and clarify the main technical and operational challenges of offshore hydrogen production. Initiatives such as the *Sealhyfe* and PosHYdon projects have taken the first steps in testing offshore hydrogen generation using PEM electrolysis systems, identifying key challenges and deriving valuable lessons.

The **PosHYdon** project aims to demonstrate the integration of three energy systems in the Dutch North Sea: offshore wind, offshore natural gas, and offshore hydrogen. It involves installing a hydrogen production unit on the Q13a-A platform, operated by Neptune Energy, which will serve as a testbed for producing hydrogen directly from offshore renewable electricity and seawater under real marine conditions (Figure 27). The Q13a-A platform is the first fully electrified offshore platform in the Dutch North Sea, located approximately 13 kilometers off the coast of Scheveningen (The Hague). The process of producing green hydrogen begins with the conversion of seawater into demineralized water directly on the platform. Electricity generated by offshore wind turbines is used to power the hydrogen production unit installed on the existing operational gas platform Q13a-A, where seawater is purified and then converted into hydrogen through electrolysis. The pilot system is designed to produce up to 400 kilograms of green hydrogen per day using a 1 MW electrolyzer. The main objective of the project is to gain hands-on experience in integrating existing offshore energy systems and producing hydrogen under real marine conditions. Additionally, the project will test the performance of the electrolyzer under variable power supply from offshore wind farms, while simultaneously collecting data on installation and maintenance costs of offshore hydrogen facilities. The green hydrogen produced on the platform will then be blended with natural gas and transported to shore via the existing gas pipeline. If the project proves successful, the use of existing offshore oil and gas infrastructure could significantly accelerate the deployment of green hydrogen production at sea, while avoiding the need to construct new offshore structures (https://poshydon.com/en/home-en/).

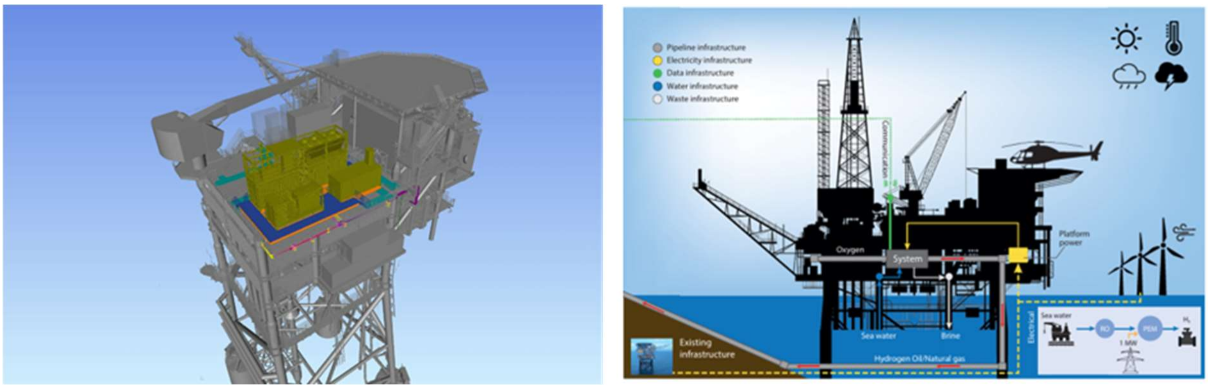

Figure 27 ***Planned layout of the gas platform in the PosHYdon project*** *– the image on the left shows the placement of installations on the gas platform, while the image on the right presents a schematic diagram of the process. Source: https://www.prnewswire.com/news-releases/dutch-state-joins-offshore-green-hydrogen-pilot-poshydon-via-ebn-302016835.html; https://www.gceocean.no/media/3884/211020-maritime-hydrogen-and-marine-energy_poshydon.pdf*

The **CrossWind BLPH** Project aims to build and test a pilot Base Load Power Hub (BLPH) within the Hollandse Kust Noord CrossWind offshore wind farm, integrating an approximately 2.5 MW electrolyzer, a 1 MWe battery energy storage system (BESS), a 1,200 kg hydrogen storage tank, a 1 MWe fuel cell, and 0.5 MW of floating solar panels. The wind farm consists of 69 turbines, each with a capacity of 11 MW. In May 2025, installation of the anchoring system for the world's first offshore solar farm located within a wind park was completed. The anchoring system will hold the floating solar farm in place, while an electrical cable connects it to the foundation of a nearby wind turbine (https://www.crosswindhkn.nl/news/2025/04/offshore-solar-integration-with-offshore-wind-is-kicking-off-in-the-netherlands/. This installed project of an offshore solar farm within a wind park demonstrates the enormous potential of combining solar and wind energy, where the hybrid setup ensures a more stable electricity supply to shore and can increase the total energy output up to fivefold, using the same marine area.

The **Sealhyfe** Project, located off the coast of Le Croisic, France, focused on the production of green and renewable hydrogen with a production capacity of approximately 440 kg of hydrogen per day, using a 1 MW PEM electrolyzer powered by electricity generated from a floating wind turbine (Figure 28). The project was successfully completed in the first quarter of 2024, with the produced hydrogen being released into the air during the testing phase. The main goal of the project was to demonstrate the feasibility and reliability of offshore green hydrogen production, proving that an electrolyzer can operate efficiently and safely in harsh marine conditions, thereby paving the way (https://hydrogeneurope.eu/europes-first-offshore-h2-pilot-saw-electrolyser-performance-as-high-as-on-land/).

Figure 28 ***Right:*** *Sealhyfe, pilot project for offshore hydrogen production (Lhyfe) equipped with a Plug electrolyzer, installed on the* ***WAVEGEM*** *platform (GEPS Techno).* ***Left:*** *Floating wind turbine* ***FLOATGEN*** *(BW Ideol) at the* ***SEM-REV*** *offshore test site (Centrale Nantes / OPEN-C). ©Lhyfe Source: https://www.lhyfe.com/press/lhyfe-reviews-the-results-of-the-sealhyfe-project-the-worlds-first-offshore-hydrogen-production-pilot-objectives-met-and-progression-to-an-unprecedented-level-of-operational-excellence/*

In the **Hydrogen Offshore Production for Europe** (**HOPE**) project, green hydrogen will also be produced offshore and transported to shore via a composite pipeline. The planned production capacity is around 4 tonnes of green hydrogen per day, corresponding to an electrolyzer capacity of approximately 10 MW. However, unlike other offshore concepts, in this case the electrical power generated by wind will be supplied from onshore through a subsea cable, while the produced hydrogen will be returned to shore through a flexible composite hose (Figure 29). The HOPE project will be in the North Sea, approximately 1 km off the port of Oostende, Belgium (https://hope-h2.eu/#project).

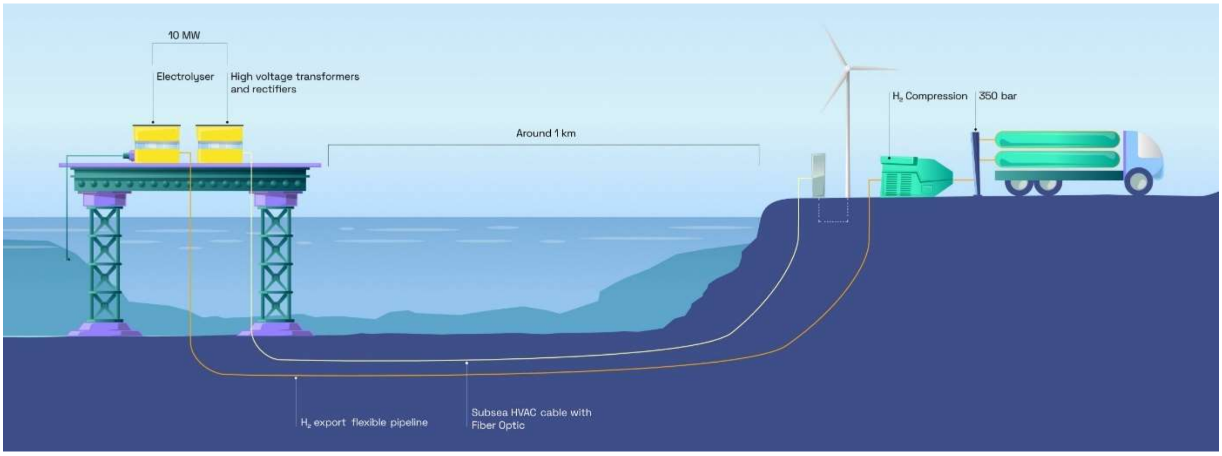

Figure 29 Schematic representation of the connectivity of structural elements in the HOPE project. Source: https://hope-h2.eu/#project

The **OYSTER** project focused on the development and demonstration of an offshore PEM electrolyzer specifically designed for integration with offshore wind turbines and for optimizing the efficiency of offshore wind-to-hydrogen systems. The project's primary objective was to develop compact electrolyzer systems capable of withstanding harsh offshore conditions, requiring minimal maintenance, while meeting the cost and performance targets necessary for low-cost hydrogen production.

The results obtained are intended to support future large-scale system design studies, including innovations aimed at reducing costs and improving efficiency (https://oysterh2.eu/).. The OYSTER project was carried out at the Grimsby site in the United Kingdom.

The **H2opZee** demonstration project is driven by the concept of constructing a 300–500 MW electrolyzer located far offshore to produce green hydrogen in the Netherlands (Figure 30). The hydrogen produced would then be transported to shore via an existing natural gas pipeline, with a capacity of 10–12 GW, already suitable for future expansion of green hydrogen production. H2opZee consists of two phases: the first phase involves conducting a feasibility study and establishing an accessible knowledge platform, aiming to initiate offshore hydrogen production in the Netherlands. The second phase will focus on actual implementation, with the public tender methodology for that phase still to be defined. The feasibility study was planned to begin in Q2 2022 (https://www.rwe.com/en/press/rwe-renewables/2022-02-15-rwe-and-neptune-energy-join-forces-to-accelerate-green-hydrogen-production-in-dutch-north-sea/).

*Figure 30 Schematic layout of infrastructural elements in the **H2opZee project**. Source: https://www.rwe.com/en/research-and-development/hydrogen-projects/h2opzee/*

The innovative research project **SENSE-HUB** focuses on the integration of multiple offshore energy modules in the Dutch sector of the North Sea. The project explores the synergies between offshore wind farms, offshore solar systems, and offshore hydrogen production, while also assessing administrative and regulatory barriers that could be removed to accelerate implementation. The main activities include demonstration of an optimized offshore solar system in the North Sea and Environmental monitoring and modelling to better understand the impacts of hybrid energy parks. The project is linked to the Q13a offshore production platform, serving as a testing and demonstration site for integrated offshore energy systems.

According to available data (https://www.infobuildenergia.it/approfondimenti/eolico-offshore-italia-idrogeno/), Italy has introduced the **HyMed** project, presented as the world's largest floating offshore wind and green hydrogen initiative, with an expected capacity of 3.2 GW by 2027 in the country's ultra-deep waters. The project is being developed by the British operator Aquaterra Energy and the Dutch company Seawind Ocean Technology. It is expected to generate 3.2 GW of electricity, of which over 1 GW will be converted into green hydrogen. The Dutch operator explains its decision to build such a facility in the Mediterranean as being based on the region's optimal conditions for large-scale offshore wind projects and its potential to foster cross-border synergies serving both Europe and the Middle East–North Africa region (MENA).

However, this is not the only project underway in Italy. According to the Italian Maritime Spatial Management Plan (*Piano di gestione dello spazio marittimo Italiano*) (https://www.sid.mit.gov.it/documenti-piano), specifically Appendix III, numerous initiatives and projects are currently in progress. As of 31 December 2023, applications for connection to offshore wind installations across the country totalled over 91 GW of installed capacity. For the Adriatic maritime area, the Ministry of Environment and Energy Security (MASE), as the competent authority, received a total of 25 offshore wind farm proposals, with a combined installed capacity of approximately 25 GW.

ULTFARMS is a pioneering Horizon Europe Ocean Mission project aimed at transforming and scaling up low-trophic aquaculture (LTA), such as seaweed and shellfish cultivation, within offshore wind farms located in the North and Baltic Seas. The project is designed to optimize the production of these organisms by integrating innovative engineering, technical, ecological, and biological processes into a profitable, sustainable, and environmentally friendly value chain. By embedding low-trophic aquaculture systems within offshore wind farms, the project seeks to deliver environmentally responsible and commercially viable aquaculture products. As a result, new cultivation structures and systems are expected to be developed, featuring ecologically sustainable designs. The project began in 2023, with results scheduled for publication in 2026. (https://ultfarms.eu/about/) (Figure 31).

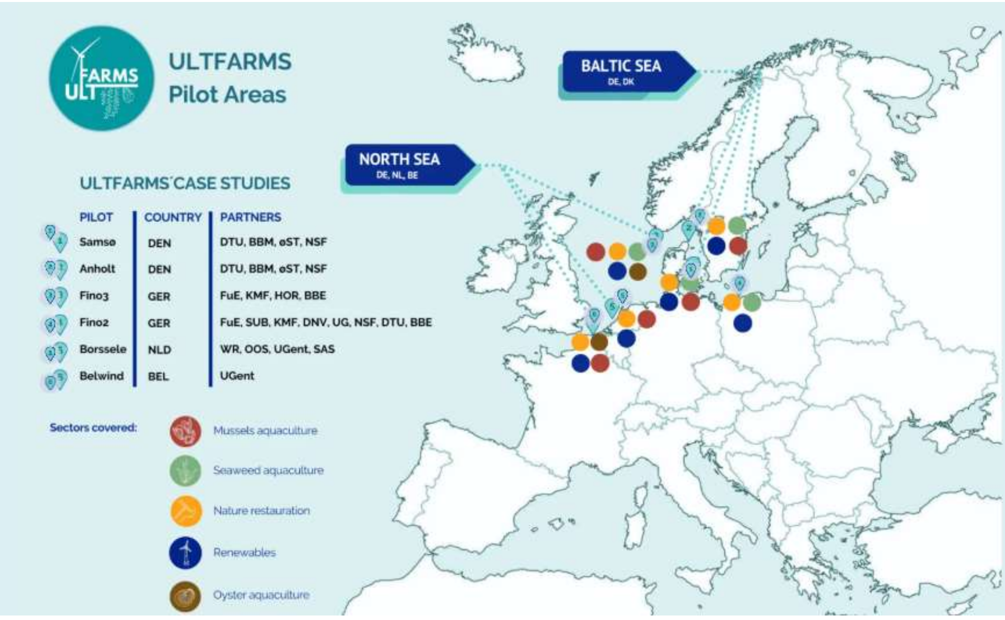

Figure 31 Areas of implementation of the ULTRAFARMS project Source: https://ultfarms.eu/pilots/

The project is being implemented across six locations, each focusing on different low-trophic species. At Location 1, Samsø (Denmark), the pilot project is centred on mussel cultivation using a new farm structure design that combines net and tubular elements, providing enhanced resistance to waves and marine currents (Figure 33). At

Location 3 – Fino 3 (Germany), in addition to the cultivation of mussels and seaweed, efforts are also being made to reintroduce oysters, a species that was once dominant in the area but is now functionally extinct (Figure 32).

Figure 33 area Fino 3, Germany Source: https://ultfarms.eu/fino3-summer-update/

Figure 32 Pilot area Samsø (Denmark) Source: https://ultfarms.eu/samso-pilot-update-may-2024/

Norther, a Belgian offshore wind farm located in the North Sea, is participating in a unique large-scale seaweed cultivation project (https://www.norther.be/offshore_seaweed_farm/). Within this initiative, the Wier & Wind consortium has launched a pilot project aimed at testing the feasibility of integrating seaweed cultivation between the wind turbines. The objective is to explore how offshore renewable energy production can be synergistically combined with sustainable aquaculture, promoting a multi-use approach to marine space that enhances both ecological value and economic potential.

In recent years, several small-scale seaweed cultivation initiatives have been launched across Europe, mostly in coastal areas. However, coastal sites alone are insufficient to meet the growing global demand for seaweed. Offshore wind farms offer a suitable alternative, as the large, unused spaces between turbines can be utilized for the sustainable production of food such as seaweed, thereby ensuring optimal use of available marine space. Nevertheless, no consensus has yet been reached on which cultivation methods are most appropriate under offshore conditions. These sites are exposed to strong waves and marine currents, while limited accessibility further increases the costs of vessel operations, making automated monitoring and harvesting systems almost essential.

To address these challenges, the *Wier & Wind* consortium has developed a new cultivation system, along with innovative seeding techniques and harvesting machinery equipped with remote monitoring capabilities (Figure 34). The project also enabled the testing of various net types, seeding methods, and nursery systems for the growth of brown algae under offshore conditions. In doing so, it contributes to the transition toward a circular and sustainable blue economy in the North Sea region and aligns perfectly with investors' strategies focused on sustainability and the multifunctional use of marine space.

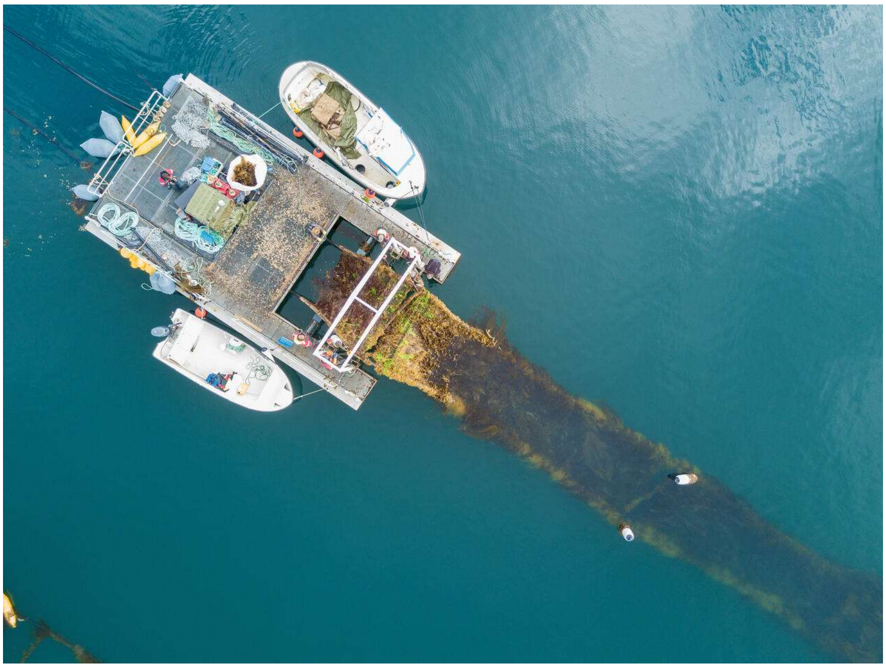

Figure 34 Cultivation of seaweed in the "Norther" project at the N location of the wind farm Source: https://interregvlaned.eu/wier-wind/over-ons

Through the **OFFWOFF** (Offshore Floating Wind and Offshore Fish Farming) project, researchers explored the coexistence potential of offshore wind energy and marine aquaculture within the same maritime space — specifically focusing on salmon farming. This approach highlights the potential of multifunctional solutions, where different sectors and interests can coexist and complement one another within a shared marine environment (Figure 35). The project included comprehensive analyses of metocean conditions, hydrodynamic performance, underwater noise, coexistence feasibility, and business potential. The results demonstrated that floating wind turbines and underwater fish farms can operate side by side with minimal interference, with the only requirement being the addition of three mooring lines positioned opposite the SubFarm system as a safety measure.
The innovative SubFarm system enables dynamic submersion of fish cages, optimizing biological conditions while reducing exposure to storms, predators, and parasites (Figure 35). Using the Mareld project in the Skagerrak as a

pilot study, the project confirmed that combined production of renewable energy and farmed Atlantic salmon is technically feasible, biologically sustainable, and economically attractive. A total of four SubFarm locations are planned, each projected to produce 12,000 tonnes of fish annually (Freja Offshore, Subfarm, ÅKP and Fyrbodal's Association of Local Authorities, 2025).

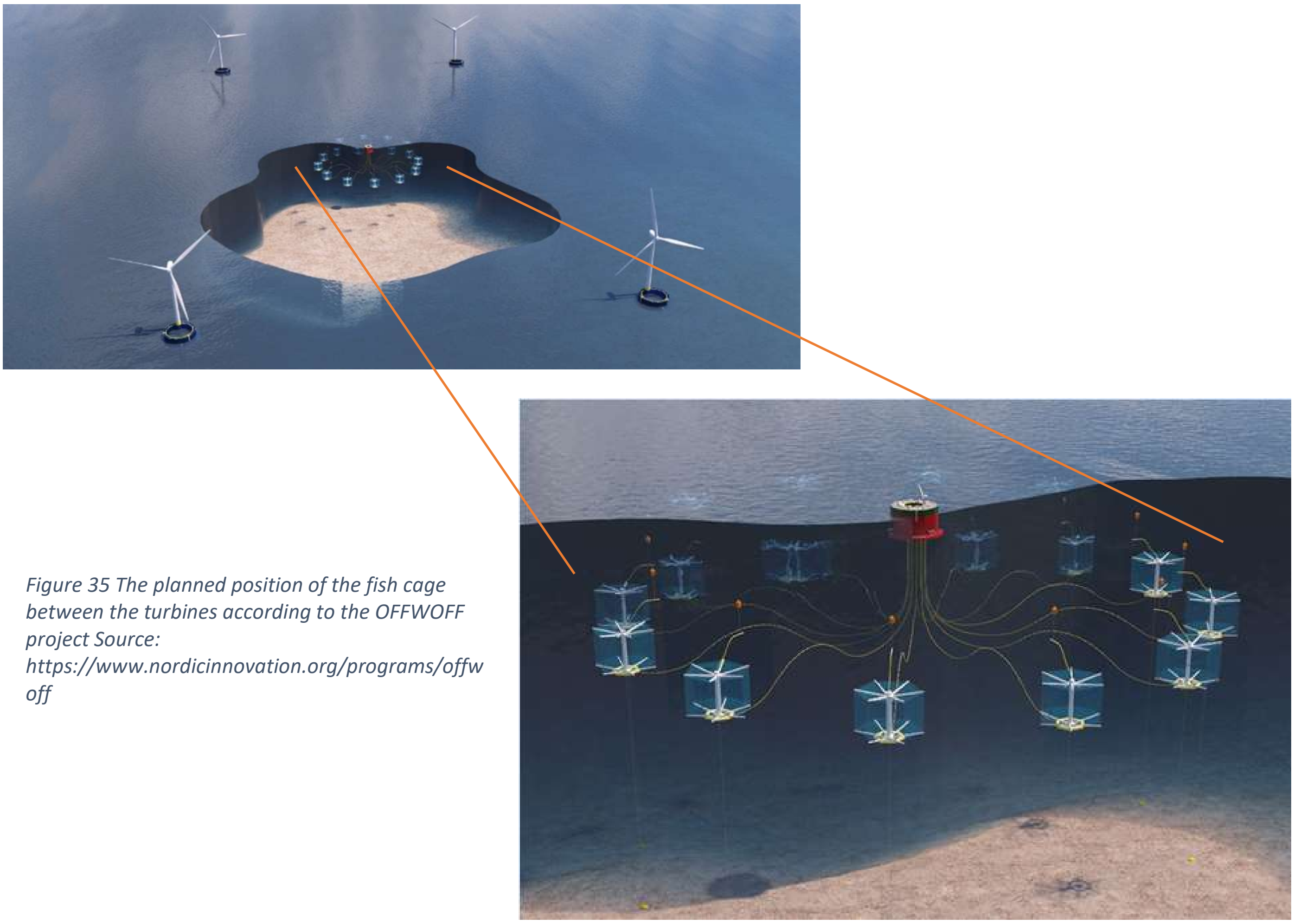

Figure 35 The planned position of the fish cage between the turbines according to the OFFWOFF project Source: https://www.nordicinnovation.org/programs/offwoff

AquaWind, co-financed by the European Maritime and Fisheries Fund (EMFF), is a European project aimed at delivering a practical demonstration of an integrated multi-use solution combining offshore renewable energy generation and aquaculture. For the first time in the Atlantic region, the AquaWind project has tested a multi-use concept that merges marine energy production with fish farming (Figure 36). On the Canary Islands (Spain), a prototype was installed integrating an enhanced version of the W2Power twin-turbine floating platform with a specially designed aquaculture cage, built from innovative net materials and equipped with a high level of digitalization for remote control and monitoring. In the first testing phase, the focus is on the cultivation of gilthead seabream (*Sparus aurata*), while the second phase will introduce the greater amberjack (*Seriola dumerili*). The objective is to demonstrate that offshore wind power generation and aquaculture can coexist and be remotely monitored within the same marine area, allowing the simultaneous cultivation of different fish species and the assessment of mutual environmental and operational impacts. The developed multi-use concept directly addresses one of the European Union's key challenges — the optimization of sustainable and efficient use of marine space. By integrating renewable energy and aquaculture at a single site, the project significantly reduces the carbon footprint while contributing to the achievement of the EU's climate and energy objectives.

Figure 36 Towing of the multi-use system to its deployment site Source: https://owcltd.com/media/news/aquawind-project-breakthrough-prototype-launch-complete/

Mingyu-1 is a Chinese offshore aquaculture project that integrates wind energy generation with fish farming, utilizing advanced artificial intelligence and big data analytics for monitoring, automated cleaning, and harvesting operations. Developed by a leading offshore energy company, the installation represents an innovative approach to combining renewable energy with sustainable fisheries. The fish cages are positioned within the lattice foundation structure of the wind turbine itself, creating a fully integrated and space-efficient multi-use system (Figure 37).

Figure 37 Placement of fish cages and aquaculture nets within the lattice foundation structure of the Mingyu-1 offshore wind farm Source: https://www.newsgd.com/node_e9dced8600/5a39cfd85b.shtml

3.9. EU & Pilot Regions Critical Infrastructure Context

The European gas pipeline infrastructure was historically developed for the transport of natural gas, but the accelerated energy transition and the climate neutrality target for 2050 now require its adaptation and repurposing toward clean energy carriers. In this context, the European Hydrogen Backbone (EHB) initiative was launched — a collaborative effort bringing together Europe's leading Transmission System Operators (TSOs)[5]. The EHB envisions the creation of a comprehensive pan-European hydrogen network, designed to support the large-scale transport of hydrogen across borders. The EHB vision relies on a combination of repurposed natural gas pipelines and newly constructed hydrogen pipelines, with the objective of establishing by 2040 a network spanning over 28,000 kilometres, connecting key industrial clusters, ports, and regions rich in renewable energy sources. Indeed, without a developed hydrogen transmission infrastructure, there can be no sustainable hydrogen production or consumption, as the transport network serves as the essential link between production sites and demand centres, enabling the creation of a functional and resilient hydrogen market.

Therefore, the EHB initiative is fully aligned with the EU Hydrogen Strategy (2020), which emphasizes the importance of developing infrastructure for the production, transport, and storage of green hydrogen as a cornerstone for the decarbonization of heavy industry, transport, and the energy sector. It is also closely linked to the "Fit for 55" legislative package and the Gas and Hydrogen Market Reform (Gas Package 2021/2023), which for the first time introduces a clear regulatory framework for hydrogen networks. As of 2024, the new EU Regulation on the Internal Markets for Renewable, Natural and Decarbonised Gases and for Hydrogen (Regulation (EU) 2024/1789) and the accompanying Directive (EU) 2024/1788 establish rules for third-party access, tariff structures, and safety standards for hydrogen transmission infrastructure. According to the latest EHB plan, by 2040 the network is expected to expand to approximately 53,000 km, consisting of around 60% repurposed pipelines (currently used for natural gas transport) and 40% newly built hydrogen pipelines (https://ehb.eu/newsitem/european-hydrogen-backbone-grows-to-meet-repowereu-s-2030-hydrogen-targets).

The repurposing of existing methane pipelines for hydrogen transport is estimated to be 2–4 times cheaper than constructing entirely new infrastructure. Moreover, existing gas pipelines already have established routes, permits, and interconnection points, which significantly accelerates project development.

However, while conversion is technically feasible, it requires specific adaptations due to the smaller molecular size of hydrogen compared to methane. This difference increases the risk of leakage, making comprehensive inspections of joints, valves, and seals essential throughout the system. Additionally, hydrogen can affect the structural integrity and cohesion of pipeline materials, necessitating thorough cleaning, testing, and potential replacement of certain sections before operation. Furthermore, compressors and valves must be specifically designed for hydrogen, as existing components are engineered for natural gas (methane, CH_4), which has a higher density at equal volume. Therefore, equipment recalibration and redesign are required to ensure safe and efficient hydrogen transmission. Because of its lower density, hydrogen carries less mass, and therefore less energy, than methane when transported at the same volumetric flow rate (e.g., m^3/s through a pipeline). This means that a higher flow rate is

[5] TSO members EHB for Croatia is Plinacro, for Italy is SNAM

required to deliver an equivalent energy content, a factor that must be accounted for in AI-assisted or advanced flow simulations and design calculations. The EHB initiative considers hydrogen blending into the natural gas stream within existing transport infrastructure to be a suitable transitional step, particularly during the 2020s and early 2030s, before establishing dedicated hydrogen pipeline networks ((https://ehb.eu/page/country-specific-developments). The practice of blending is well-documented in the scientific literature, where studies (e.g., Lipiäinen, S et al., 2023) indicate that up to 20 vol.% hydrogen can be mixed into existing natural gas grids without requiring major technical modifications to pipelines or end-user equipment. Such hydrogen blending trials are already underway across Europe. For instance, in Germany, a 20% hydrogen–natural gas mix has been successfully tested in around 100 households, with no recorded malfunctions or safety issues in domestic energy appliances (https://www.hydrogeninsight.com/innovation/german-gas-operator-says-20-hydrogen-blending-trial-in-100-homes-has-been-100-trouble-free-after-six-months/2-1-1455488?utm).

The EHB corridor concept provides an economically viable solution for bridging the substantial regional disparities between hydrogen producers and end users across Europe. These differences arise from demographic, geographic, economic, and climatic factors, and the corridors aim to connect regions with hydrogen surpluses to those with insufficient domestic production capacity, through a system of cross-border pipeline networks. This approach is fully aligned with the objectives of the European Union, particularly within the framework of Projects of Common Interest (PCI), which promote strategic, cross-border energy infrastructure essential for the functioning of the EU internal energy market and the achievement of climate goals. According to the EHB vision, by 2030, five key cross-border hydrogen transport corridors are expected to be established, linking high-production regions with Europe's major industrial centres, ports, and planned hydrogen valleys. The proposed routes include: (A) the North Africa – Southern Europe corridor, (B) the North Africa – Southwestern Europe corridor, (C) the North Sea corridor, (D) the Nordic and Baltic corridor, and (E) the Eastern and Southeastern Europe corridor (Figure 38). While the primary purpose of these corridors is cross-border hydrogen transmission, in the initial phase, they will also function to interconnect local production and consumption hubs within various parts of Europe — laying the foundation for a fully integrated European hydrogen market.

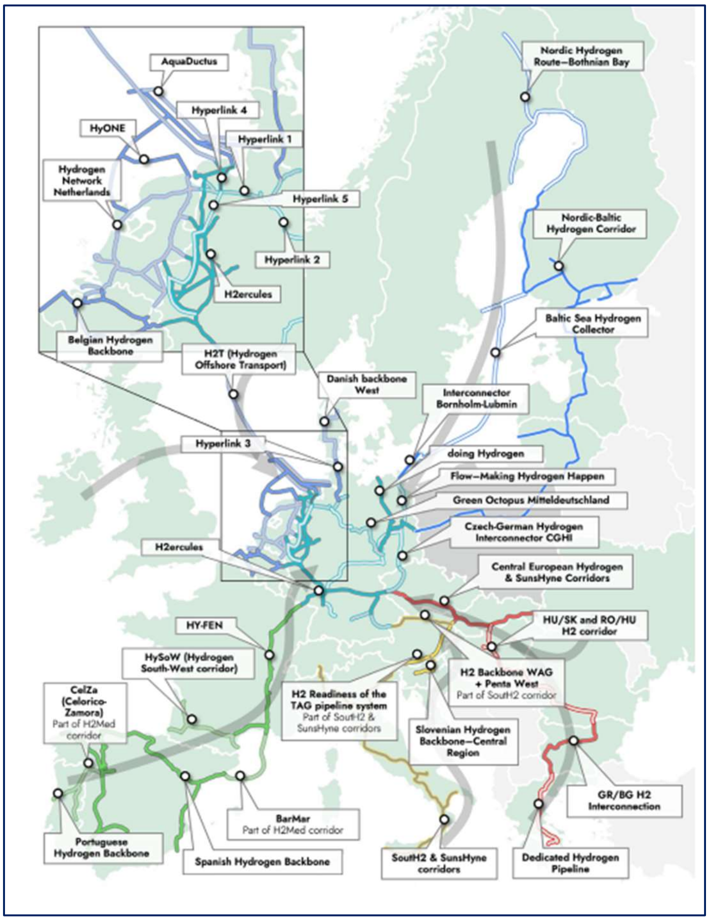

Figure 38 Overview of all EHB subprojects and five main corridors Source: https://ehb.eu/files/downloads/EHB-2023-Implementation-Roadmap-Part-1.pdf

Both Croatia and Italy form an integral part of Corridor A, which is designed to enable the transport of low-carbon hydrogen from North Africa and southern Italy toward Central Europe. In this framework, collaboration among stakeholders across the entire hydrogen value chain is essential for developing cost-competitive production zones in North Africa. At the national level, green hydrogen from North Africa will first be integrated into the Italian hydrogen network, planned to encompass approximately 2,300 km of pipelines, of which around 75% will consist of repurposed natural gas pipelines. After meeting domestic demand, hydrogen transport will continue northward toward Central Europe. In Austria, hydrogen will be used both for domestic consumption and for transmission via the repurposed TAG, WAG, and Penta West pipelines toward Germany, including connections to underground storage capacities. The route from Austria through Slovakia and the Czech Republic to Germany will rely entirely on repurposed gas infrastructure, serving major industrial and consumption centers along the corridor. A connection with the Slovenian hydrogen network is also foreseen, which will cover national demand while enabling interconnection with Croatia, facilitating regional hydrogen flow within the broader Southern and Central European corridor system (Figure 39) (Grid, A., et al., 2023, , Moultak, M. et al. 2023).

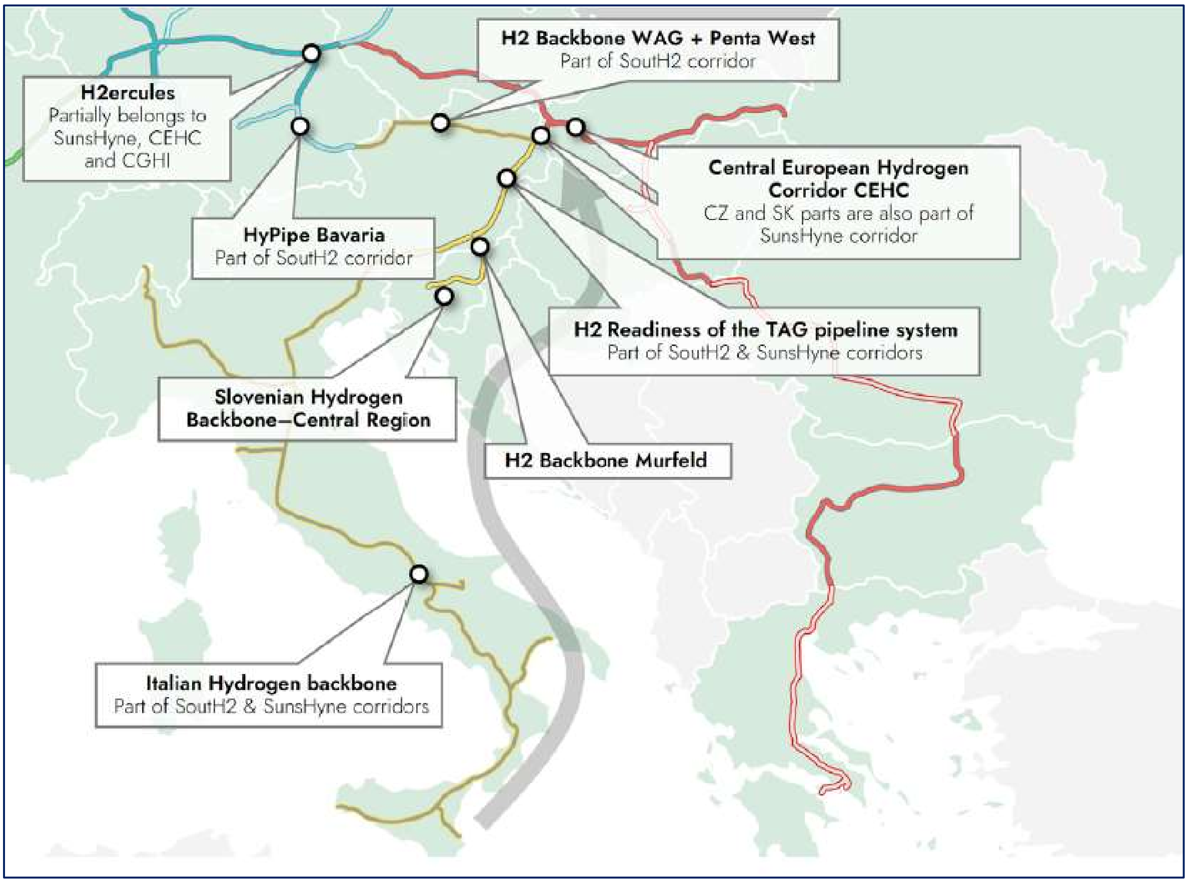

Figure 39 Planned development of Corridor A Source: https://ehb.eu/files/downloads/EHB-2023-Implementation-Roadmap-Part-1.pdf

3.9.1.Infrastructure in Italy and Potential Integration of Offshore Wind and Green Hydrogen

Currently, Italy consumes approximately 16 TWh of hydrogen per year as a feedstock for refineries and fertilizer production, representing about 1% of the country's final energy consumption. In recent years, concrete steps have been taken to expand the role of hydrogen in Italy's energy transition. For example, in June 2020, Alstom and SNAM signed an agreement to develop hydrogen-powered trains, building upon the experience gained with hydrogen trains already in operation in northern Germany. Similarly, in June 2019, Toyota and ENI announced a partnership to accelerate the rollout of hydrogen refuelling stations and the use of hydrogen vehicles in Italy. Projections for hydrogen use in the transport sector are particularly ambitious, especially considering that Italy currently has no operational hydrogen refuelling stations. However, ENI is developing two pilot stations, one located in San Donato Milanese and another in the Venice area, marking the first steps toward establishing a national hydrogen mobility network (Lambert, M. et Schulte, S., 2021.).

Today, Italy stands at a pivotal point in its energy transition, with the development of offshore wind farms and green hydrogen technologies increasingly recognized as strategic national priorities. The country's geographical position and abundant natural resources, particularly the strong and consistent winds in the Adriatic and Tyrrhenian

Seas, create favourable conditions for offshore electricity generation. At the same time, the European Union is setting ambitious decarbonization targets through the Fit for 55, the Renewable Energy Directive (RED III), and the EU Hydrogen Strategy, all of which Italy is aligning with in its national energy planning. Policy frameworks such as the *Piano Nazionale Integrato per l'Energia e il Clima (PNIEC*), the *Strategia Nazionale Idrogeno*, and the *Maritime Spatial Management Plan (Piano di Gestione dello Spazio Marittimo*) clearly emphasize the need to integrate offshore renewable energy into the broader national energy system, while simultaneously linking it with the development of green hydrogen value chains.

Currently, the proposed technical approaches for integrating offshore wind farms and hydrogen technologies in Italy are based on two main configurations: electricity transmission to shore, where the generated power is transported via submarine cables and used to supply onshore electrolyzers and Offshore hydrogen production, where electrolyzers are installed directly at sea, either on floating or fixed platforms located near the wind turbines. Each option offers distinct advantages and challenges, onshore electrolyzers benefit from existing infrastructure, easier access for maintenance, and simpler grid connection and regulatory procedures, while offshore electrolyzers, on the other hand, reduce the load on the onshore power grid, enable direct conversion of electricity into hydrogen at the generation site, and minimize transmission losses. This setup also allows for flexible operation: hydrogen can be produced either by using the full electricity output of the wind farm or only during periods of excess generation, when power production exceeds consumption or grid capacity. In this way, hydrogen serves as a flexible energy storage medium, helping to balance the overall energy system and enhance grid stability while supporting the decarbonization of multiple sectors.

Italy possesses one of the most advanced gas pipeline networks in Europe, extending over 30,000 kilometers and already integrated into cross-border energy flows between Southern and Central Europe. Thanks to its geostrategic position, Italy plays a pivotal role in linking Mediterranean renewable energy sources, including the potential production of green hydrogen in North Africa, with industrial and consumption centers in Central and Western Europe. The Italian Hydrogen Strategy envisions an extensive repurposing of the existing gas infrastructure as part of the *Italian Hydrogen Backbone initiative* (https://www.south2corridor.net/?utm_source), under which a significant portion of the current pipeline system will be adapted for hydrogen transport. Specifically, SNAM plans to develop a hydrogen pipeline network of approximately 2,300 km by 2030, of which about 75% will consist of repurposed natural gas pipelines, while the remaining 25% will be newly constructed. This approach enables Italy to simultaneously meet its domestic hydrogen demand and position itself as a major transit hub within the framework of European hydrogen transport corridors, strengthening its role as a key connector between North Africa and Central Europe in the future hydrogen economy (Figure 40). The project also includes investments in compressor stations with a combined capacity of several hundred megawatts, enabling the pipeline network to withstand the higher pressures required for hydrogen transport. Due to its strategic geographic position, Italy is expected to play a dual role — both as an importer of green hydrogen, particularly from North Africa, and as a key hub connecting ports, industrial centers, and storage facilities within the broader European hydrogen network. This hydrogen backbone will not only satisfy domestic demand but will also facilitate the transit of hydrogen toward Central and Northern Europe, strengthening Italy's role as a southern gateway in the pan-European hydrogen corridor system. The repurposing of existing gas infrastructure aligns with Italy's national strategies, *the Piano Nazionale di Ripresa e Resilienza (PNRR) and the Strategia Nazionale Idrogeno*, both of which outline the progressive conversion of portions of SNAM's pipeline network to enable the transport of pure hydrogen, thereby contributing to Italy's energy transition and decarbonization goals.

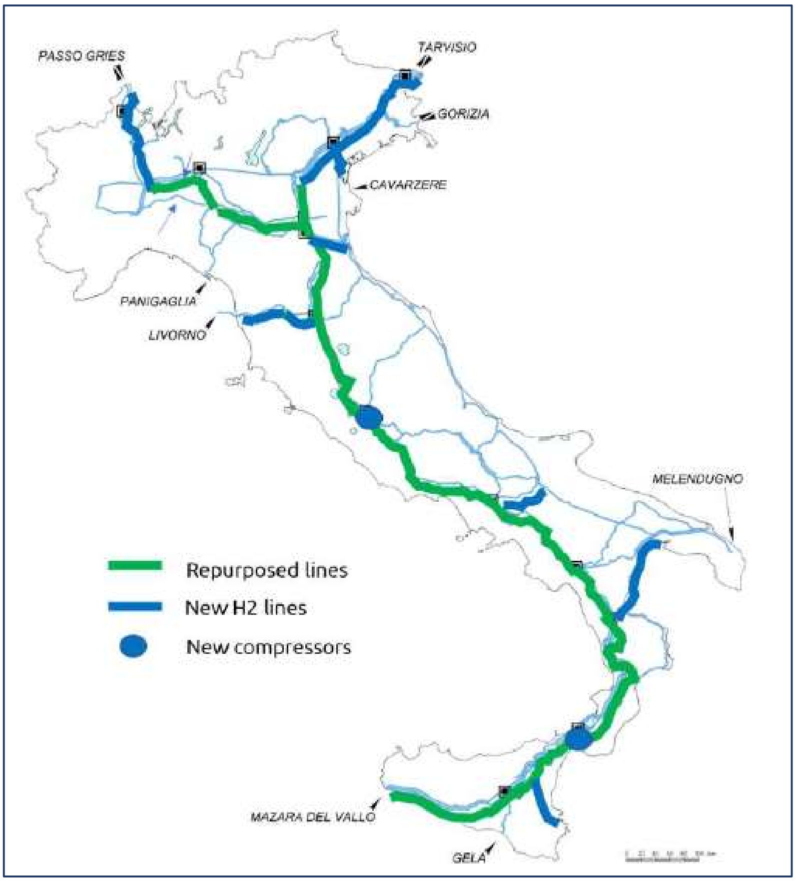

Figure 40 SNAM projects for Italian H2 Backbone, display new and repurposed pipeline Source: SNAM 2030 vision and 2021-2025 plan

Like Germany, Italy is also advancing pilot projects involving hydrogen–natural gas blending in its gas networks — both for residential and industrial applications. For instance, in the town of Castelfranco Emilia, a pilot project has been launched introducing approximately 5% hydrogen into the natural gas mix within part of the local residential distribution network, with plans to increase the hydrogen share to 10% in the near future (https://www.rinnovabili.net/tech-innovations-and-startups/energy-tech-innovations-and-startups/hydrogen-gas-blend-italy-launches-5-test-in-gas-network/?utm). In May 2025, it was also announced that Italgas (IG.MI) and EDF's Edison Energia (EDNn.MI) had signed an agreement to supply a green hydrogen–natural gas blend to the Granarolo food processing plant in Sardinia. This initiative represents Italy's first industrial-scale trial using a mixture containing up to 20% green hydrogen, where the hydrogen production energy will be sourced entirely from renewable power generated by an Italgas-owned plant on Sardinia https://www.reuters.com/business/energy/italgas-edison-test-green-hydrogen-an-industrial-plant-2025-05-15/?utm).These projects demonstrate Italy's progressive approach toward integrating hydrogen into existing gas networks, paving the way for broader sectoral decarbonization and future-scale deployment of dedicated hydrogen infrastructure.

In addition to the hydrogen pipeline system, an efficient and sustainable deployment of green hydrogen production and consumption also requires a well-developed electricity transmission network. Italy operates one of the largest power grids in Europe, spanning over 70,000 kilometers of transmission lines managed by the national grid operator Terna. This network plays a crucial role in integrating renewable energy sources, particularly as the country experiences a rapid increase in installed wind and solar capacity and prepares to meet the electricity demand for powering electrolyzers. To achieve these goals, substantial investments are needed in grid reinforcement, smart management systems, and cross-border interconnections. Such developments will make the electric grid complementary to the hydrogen pipeline network, enabling flexible and stable energy transmission both within Italy and to other EU Member States. In March 2025, Terna unveiled its new 10-year development plan, outlining investments exceeding €23 billion in electricity infrastructure, focusing on grid modernization, integration of renewables, and enhanced interconnectivity to support the emerging hydrogen economy and the broader energy transition objectives (https://download.terna.it/terna/Terna_2024_2028_Industrial_Plan_Update_Presentation_8dd6bbb54c7b644.pdf) (Figure 41).

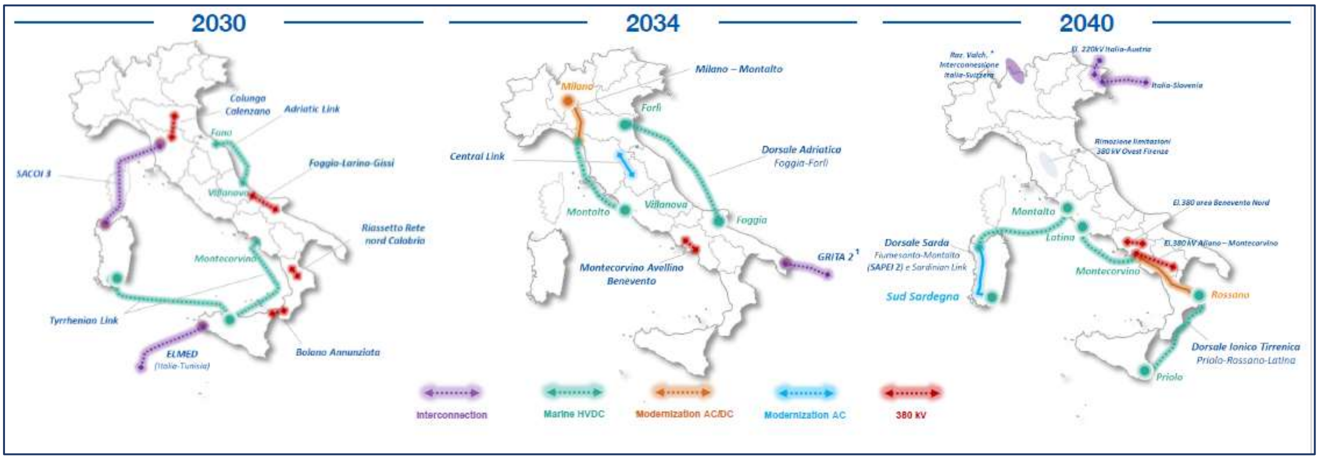

Figure 41 Terna's main strategic projects, and an overview of the main inter-zonal initiatives and interconnections with foreign countries Source: https://download.terna.it/terna/Terna_2024_2028_Industrial_Plan_Update_Presentation_8dd6bbb54c7b644.pdf

The current Italian electricity transmission network serves as a fundamental pillar of the national energy transition, particularly in the context of green hydrogen deployment. As illustrated in the following figures (Figure 42 and Figure 43), Italy's high-voltage transmission infrastructure is robust and well-integrated, ensuring reliable power delivery across the country. At the same time, the distribution connections to end-users enable the efficient utilization of renewable energy sources and provide essential support to the infrastructure required for green hydrogen production. Together, these interconnected systems, the power grid and the hydrogen network, will form the backbone of Italy's future decarbonized energy ecosystem, ensuring flexibility, stability, and resilience in line with the European Union's clean energy and climate neutrality goals (Figure 42 and Figure 43).

Figure 42 Map of the high voltage network (380 kV) in Italy Source: https://www.geni.org/globalenergy/library/national_energy_grid/italy/italiannationalelectricitygrid.shtml

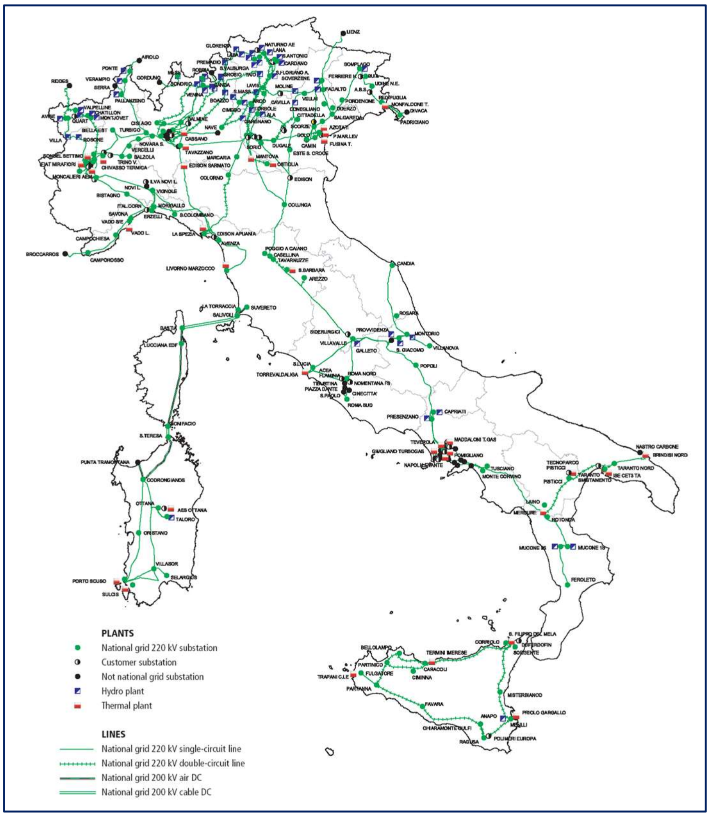

Figure 43 Map of the high voltage network (220 kV) in Italy Source: https://www.geni.org/globalenergy/library/national_energy_grid/italy/italiannationalelectricitygrid.shtml

Although the existing onshore electricity grid in Italy is generally adequate, the development of new offshore wind farms will require targeted upgrades and adaptations to ensure reliable and efficient power transmission. According to Terna's development plans, such modernization measures are already foreseen and include the construction of 275 kV underground transmission cables connecting the landfall joint place, where submarine cables meet onshore cables, to the onshore transformer station. Adjacent to this station, a 380 kV underground transmission line is also planned, linking the transformer station to the main electrical substation, with the option to extend the connection via an overhead power line if necessary. Offshore, in addition to the wind turbine structures, it is essential to include additional components, such as an offshore electrical substation, which may be fixed to the seabed or mounted on a floating platform. Without such a substation, power would have to be transmitted directly from each turbine to the onshore connection point, leading to several disadvantages, including the need for a greater number of export cables, wider cable corridors, and higher energy losses due to transmission at lower voltage levels. The primary function of the offshore substation is precisely to step up the voltage before transmission, thereby reducing losses and improving overall system efficiency. In addition to the installation of offshore substations, it is also necessary to consider the total length of the cable network, which includes interconnections between all turbines, the link to the offshore substation, and the export connection to the onshore joint bay. This cumulative cable length represents a major technical and financial component of offshore wind farm development and requires detailed spatial and environmental planning.

Furthermore, for the efficient and sustainable management of green hydrogen value chains, the development of port infrastructure must be recognized as a key element in the advancement of the marine energy sector. Italian ports already play a central role in transport and trade, but their strategic importance will increase significantly in the context of energy and climate transition. In addition to serving as primary logistics hubs for goods and passengers, ports will increasingly evolve into strategic energy centres where green hydrogen and other clean energy carriers will be produced, stored, and distributed. Planning this development requires careful consideration of spatial constraints, bathymetry, and navigational safety, ensuring secure access, efficient handling operations, and minimized congestion risks. Beyond their energy and transport roles, ports will also become drivers of industrial and innovation clusters in their hinterlands, fostering the development of renewable energy technologies, hydrogen-related manufacturing, and research and innovation ecosystems that can support the broader decarbonization and blue economy objectives. At the same time, plans are being developed to strengthen the resilience of ports to climate change through infrastructure adaptation to rising sea levels and extreme weather events. The overall development of Italian ports will also be directed toward progressive decarbonization of port operations, achieved through shore-side electrification, integration of renewable energy sources, and a transition to low-carbon fuels for vessels and port machinery. Furthermore, several Italian ports will be integrated into the *Italian Hydrogen Backbone* as an essential component of the Trans-European Transport Network (TEN-T). This integration will enable them to become key nodes in both regional and European green energy supply chains, supporting hydrogen logistics, storage, and distribution.

In this role, ports will act as strategic gateways for import and export of green hydrogen, especially through connections with North African projects and domestic renewable energy production sites, as illustrated in Figure 41.

The first pilot projects and planned locations for offshore wind and hydrogen development in Italy demonstrate a clear focus on the Adriatic Sea and the southern regions of the country, particularly Puglia, which is increasingly emerging as a strategic energy hub. In these areas, the integration of offshore wind farms with hydrogen infrastructure is foreseen, while ports play a dual role, serving as entry and exit points for goods and energy, and as logistical centres for emerging energy technologies. Consequently, the future development of ports involves not only the adaptation of port areas for hydrogen production, storage, and distribution, but also the integration of renewable energy sources and the reduction of port-related emissions through shore electrification and the transition to clean fuels.

Furthermore, Italy's strategic shift toward hydrogen, its commitment to national policy objectives, and its focus on practical, sustainable energy transition measures are evident in the officially published national development plans. These plans already identify the locations of future hydrogen production plants, planned refuelling stations, and even specify railway lines to be converted to hydrogen propulsion (Figure 44).

Ultimately, the integration of offshore wind farms and green hydrogen technologies brings a range of economic and social benefits. Italy can leverage investments in this sector to develop new industrial capacities, create jobs, and strengthen its competitiveness. At the same time, such projects contribute to energy security and reduced dependence on fossil fuels, while collaboration with Mediterranean partners, such as North African countries, opens opportunities for future hydrogen imports and the establishment of cross-border energy corridors.

However, Italy also faces numerous challenges. Technical issues such as the construction of submarine cables, the installation of offshore substations, the reliability of technologies, and the long-term storage of hydrogen must be addressed in a systematic and coordinated manner. Environmental considerations, including the protection of marine ecosystems, Natura 2000 areas, biological protection zones, and cultural heritage sites, must be carefully aligned with energy projects to avoid conflicts and ensure sustainability. In addition, continuous research and innovation are essential to make technologies such as floating wind turbines and large-scale electrolyzers both technically reliable and economically competitive.

Overall, Italy has a unique opportunity to shape a new energy model based on renewable sources, innovation, and international cooperation through the integration of offshore wind farms and green hydrogen. Such an approach could position the country at the forefront of Europe's energy transition, while simultaneously laying new foundations for sustainable development and regional stability.

The pilot areas in the Veneto region, located in the northern Adriatic, hold particularly promising potential, as they enable the direct integration of green hydrogen production with the maritime sector. Hydrogen produced in these sites could be used as fuel for ships through offshore refuelling points, allowing vessels to refuel at sea without entering ports. This would reduce pressure on port infrastructure, speed up logistics, and facilitate the broader adoption of clean fuels in maritime transport. In addition, the produced hydrogen can be immediately stored and transferred into specialized tankers, which could then transport it to other ports and industrial centres in Italy and across Europe. In this way, Veneto has the potential to develop into a key energy and logistics hub, connecting offshore renewable energy production with international supply chains and global energy markets.

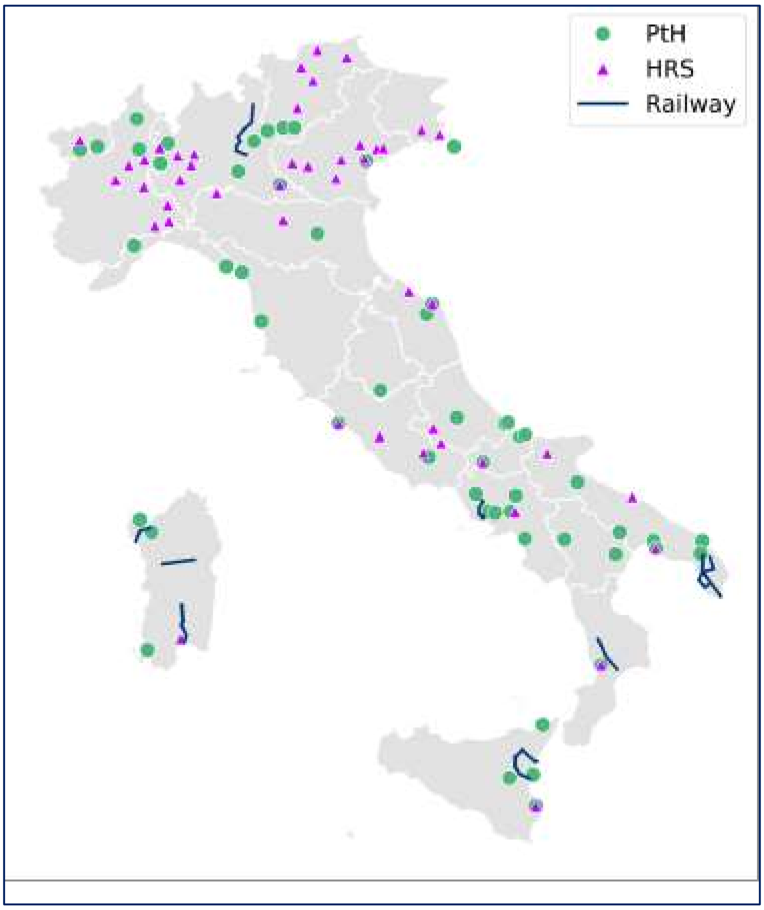

Figure 44 Future locations in Italy for hydrogen production plants (green dots), planned hydrogen refuelling stations for road transport (purple triangles), and railway lines to be converted to hydrogen (blue lines) Source: Gandiglio, M. et Marocco, P. (2024.)

In line with ongoing efforts to advance the energy transition in the Veneto region, the planned development of offshore testing and production zones is foreseen in the northern area, specifically within zones A/2 and A/7 (Figure 15). As shown in Figures 42 and 43, the 380 kV high-voltage transmission network, as well as the 220 kV grid, are located relatively close to the coastline in this region. This means that the distance between existing grid nodes and the future connection points for the cables coming from offshore wind farms is relatively short, which represents a significant advantage in terms of technical feasibility and connection costs.

In addition, it should be emphasized that the infrastructure in the Veneto region is well developed and spatially balanced: the ports are favourably distributed (Figure 14), and plans already include future refuelling stations for road transport using hydrogen or electricity (Figure 44).

The location of the designated zones is also advantageous, as they are situated within areas marked G (general use) and P (marine transport) (Figure 16). According to the spatial plan, particularly within the A/7 zone (Figure 15), it is possible to plan the development of renewable energy production activities, while also highlighting the promotion of aquaculture activities in parts of the area located within territorial waters. This combination of different uses and development possibilities confirms the hybrid potential of this region, positioning it as a promising area for the integration of renewable energy, hydrogen production, and sustainable marine resource management.

Another positive aspect lies in the fact that the share of protected areas within this zone is very low, generally up to 1% (Figure 9), which reduces potential environmental conflicts during the planning and implementation phases of future projects. On the other hand, certain challenges remain, primarily related to migratory bird species. According to the sensitivity maps shown in Figure 12, the A/2 and A/7 zones are in areas ranging from high to extremely high sensitivity with respect to bird migration routes, which presents a potential collision risk and necessitates the implementation of additional protection and monitoring measures in the future. Finally, a particularly important advantage of these zones is their proximity to the planned hydrogen pipeline, which is expected to run relatively close to the coastline (Figure 40), offering a strategic opportunity for direct integration between offshore renewable energy production and hydrogen transport infrastructure. This proximity allows for shorter transport routes for the green hydrogen produced from the designated zones to the main transmission hydrogen pipeline, resulting in lower construction costs, reduced administrative burden, and faster and more efficient project implementation. All these factors confirm that, despite certain ecological challenges, the Veneto zones represent a highly favourable area for the development of integrated energy solutions that combine offshore wind farms with green hydrogen technologies (Figure 45). In the southern part of Italy, within the Puglia region, there are three designated zones forming a connected cluster located in areas A/6 and A/9 (Figure 13). These zones are classified as general-use areas (G) (Figure 12), allowing for experimentation and application of marine renewable energy technologies, with a particular focus on wind energy. An additional advantage of the Puglia zones lies in their relatively low share of protected areas in the immediate vicinity (Figure 9), which facilitates spatial planning and reduces potential conflicts related to nature conservation. Moreover, no significant challenges related to bird migration routes have been identified (Figure 10). However, unlike Veneto, the Puglia zones are spatially more distant from transmission network nodes (Figure 42 and Figure 43). Nevertheless, the region of Puglia possesses a well-developed and robust electrical grid, which is already prepared to accommodate new renewable energy capacities, providing a solid foundation for future offshore wind and hydrogen integration projects. In Puglia, key 380 kV transmission network nodes are located near Brindisi, Taranto, and Foggia, with the grid itself connecting the south of Italy to the rest of the country and Europe. The port infrastructure in Puglia also represents a significant advantage, as the region hosts several major ports, including those in Brindisi, Taranto, and Bari (Figure 14). Particular emphasis is placed on the connection of port systems with the planned Italian Hydrogen Backbone network (Figure 40). Despite certain technical and technological challenges related to infrastructure integration, the opportunities emerging in Puglia demonstrate that the region possesses all the prerequisites to become a key hub of Italy's energy transition (Figure 45).

	Veneto	Puglia
Location and Zones	*2 zones in the north (A/2 and A/7), forming one integrated area.*	*3 zones in the south (A/6 and A/9), forming one integrated area.*
Designations under the Maritime Spatial Plan (MSP)	*Areas G (general use) and P (marine transport). In A/7, renewable energy development is permitted, along with the promotion of aquaculture within territorial waters.*	*Area G (general use), renewable energy development permitted.*
Protected Areas	*Very low share, generally up to 1%.*	*Relatively low share near the designated zones, facilitating spatial planning.*
Environmental Challenges	*High to extreme sensitivity to migratory bird routes.*	*Alignment with migratory routes and environmental policies.*
Electric Power Grid	*380 kV and 220 kV networks close to the coast; short and cost-effective connection routes.*	*Strong 380 kV nodes (Brindisi, Taranto, Foggia). Connections with Southeastern Europe: HVDC Italy–Montenegro (1 GW) and planned link with Greece. Terna foresees new investments.*
Port Infrastructure	*Good distribution of ports.*	*Major ports of Brindisi, Taranto, and Bari serve as potential energy hubs for hydrogen production, storage, and distribution.*
Hydrogen Pipeline	*Proximity to the future Italian Hydrogen Backbone; shorter and cheaper routes to the main transmission system.*	*Connection to the Italian Hydrogen Backbone planned through ports and industrial zones; linkage toward North Africa and the Mediterranean.*
Key Advantages	*Proximity to the power grid, ports, and future hydrogen pipeline; favorable balance of infrastructure benefits and low share of protected areas.*	*Southern Italy's main energy hub, with strong power grid and port connections and established international interconnections.*
Key Challenges	*Environmental risk due to migratory bird routes.*	*Alignment with environmental and landscape policies, though spatial conflicts are smaller than in the north.*

Figure 45 Summary of the strengths and challenges of developing pilot areas in Italy

3.9.2.Infrastructure in Croatia and potential integration of offshore wind farms and green hydrogen

According to the Croatian Hydrogen Strategy, the initial phase of renewable hydrogen production can be supported through the repurposing of existing industrial facilities (brownfield investments) that are either decommissioned or nearing closure but possess the potential to be converted into sites hosting new, decarbonized technologies within their production processes. In the first phase of developing green hydrogen production and consumption, the infrastructure requirements for transport are expected to be relatively modest, as production will primarily take place near or directly at the point of consumption. In subsequent stages, the hydrogen infrastructure will be expanded to serve not only industrial and transport applications, but also electricity grid balancing and the supply of heat to residential and commercial buildings. Ultimately, Croatia aims to achieve active participation in the development of the future pan-European hydrogen transport network (*Hydrogen Backbone Transmission Infrastructure*), ensuring its integration into the broader European clean energy system.

Currently, Croatia has a well-developed gas transmission and distribution system. The total length of the transmission network exceeds 2,500 km, while the distribution network extends over 18,000 km, directly supplying more than 680,000 end users across 19 of the 20 counties and the City of Zagreb. Through interconnections with Hungary and Slovenia, the Croatian gas transmission system is linked to the regional and European gas networks, while the Liquefied Natural Gas (LNG) terminal on the island of Krk, together with its evacuation pipelines, provides access to the global gas market. This configuration enables bidirectional gas flow and transport between Croatia, the region, and Europe (Figure 46). Moreover, the Croatian transmission system operator, Plinacro, is an active participant in the European Hydrogen Backbone (EHB) initiative, and national strategic documents already envisage the conversion of parts of the existing gas transmission system to enable the transport of hydrogen in the future (https://ehb.eu/page/country-specific-developments?utm_source=chatgpt.com#croatia-plinacro). According to the published data, Plinacro plans to adapt the Croatian gas transmission system to the future decarbonized gas network of the EU and has submitted a Ten-Year Network Development Plan (TYNDP) that includes five projects also integrated into the European Hydrogen Backbone (EHB) development plans. The main strategic direction of the hydrogen system's development is the repurposing and adaptation of existing gas infrastructure, combined with the construction of new hydrogen transport infrastructure where necessary. These projects include upgrading the gas transmission system to enable hydrogen blending and the transport of 100% hydrogen, and developing both national and cross-border hydrogen networks to ensure future interconnection with the European hydrogen corridor system (Figure 47) (Belamarić, B. & Bošnjak, R., 2023).

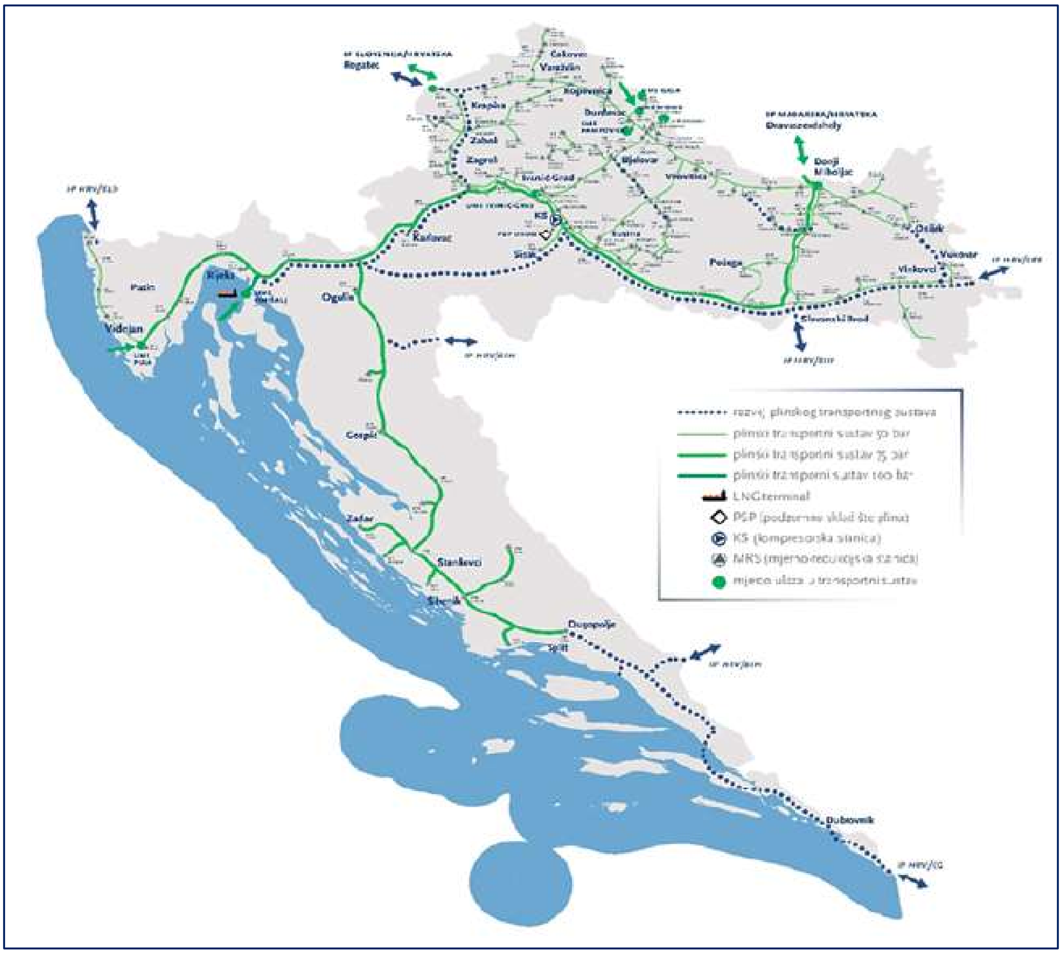

Figure 46 Gas transmission system of the Republic of Croatia Source: Belamarić, B. i Bošnjak, R., 2023

Figure 47 Overview of Plinacro's planned hydrogen projects
Source: Belamarić, B. i Bošnjak, R., 2023

At present, Croatia uses only very limited quantities of hydrogen, primarily within industrial processes and research pilot projects, and it does not yet have a developed national hydrogen network or significant production capacities. However, with the adoption of the National Hydrogen Strategy until 2050, the country has clearly recognized the need to develop hydrogen as a key component of decarbonization and the transition toward renewable energy sources. According to the Strategy, by 2030 Croatia plans to construct the first large capacity electrolyzers, launch pilot projects in the transport and industrial sectors, and integrate with regional initiatives, such as the *European Hydrogen Backbone* (EHB). In this context, the two coastal counties, Istria and Split-Dalmatia, play an especially important role, as they possess favourable natural conditions for the development of offshore renewable energy, along with strong port and energy infrastructure potential, making them strategic regions for the early deployment of integrated offshore wind and hydrogen projects.

The electricity transmission network of Croatia serves as a fundamental pillar for energy security and the integration of an increasing share of renewable energy sources. The Croatian Transmission System Operator (HOPS) manages over 7,500 kilometres of transmission lines, ranging from 110 kV to 400 kV, connecting the entire country into a unified system and ensuring cross-border interconnections with neighbouring countries (Figure 48). Over the past decade, Croatia has experienced a significant increase in the integration of wind and solar power plants, which has created a continuous need for investment in grid reinforcement and modernization, smart management systems, and the development of new balancing capacities. Documents such as the Ten-Year Transmission Network Development Plan of HOPS emphasize the need to adapt the national grid to the accelerated energy transition, including future interconnections with green hydrogen production facilities. According to the Ten-Year Transmission Network Development Plan 2025–2034, recently presented by HOPS (source link), significant investments are planned in electrical infrastructure, specifically in the expansion, reconstruction, and revitalization of the national transmission network. Excluding investments required for new grid connections, a total of approximately €1.782 billion will be invested over the ten-year period. Among the key planned activities are the preparation and initiation of the construction of a 400 kV transmission network in Istria, as well as the expansion of grid capacities in northern and central Dalmatia.

The plan also foresees the preparation and launch of investments in the construction of a 400 kV transmission network aimed at energy evacuation and improved interconnection between the coastal regions of Croatia and the main consumption centers (Rijeka, Zagreb), through the construction of new 400 kV overhead transmission lines along the Konjsko–Melina corridor (Figure 49).

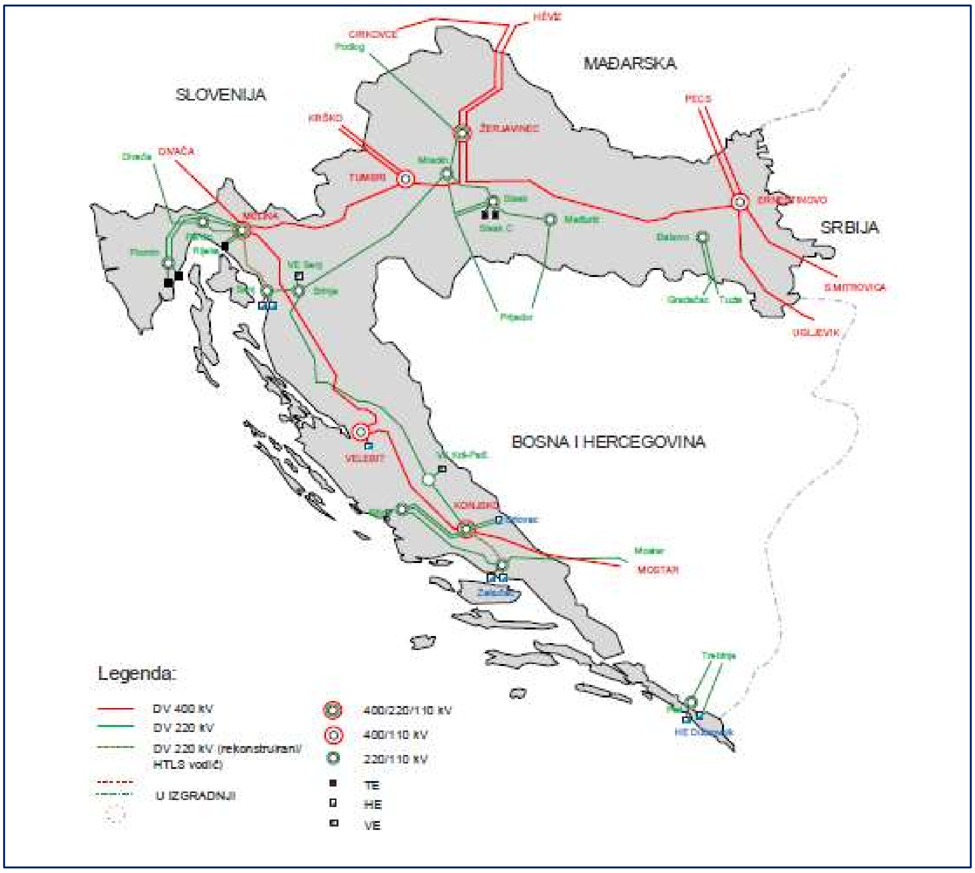

Figure 48 Configuration of the 400 kV and 220 kV transmission network in Croatia, September 2024 Source: Ten-Year Transmission Network Development Plan 2025–2034, HOPS

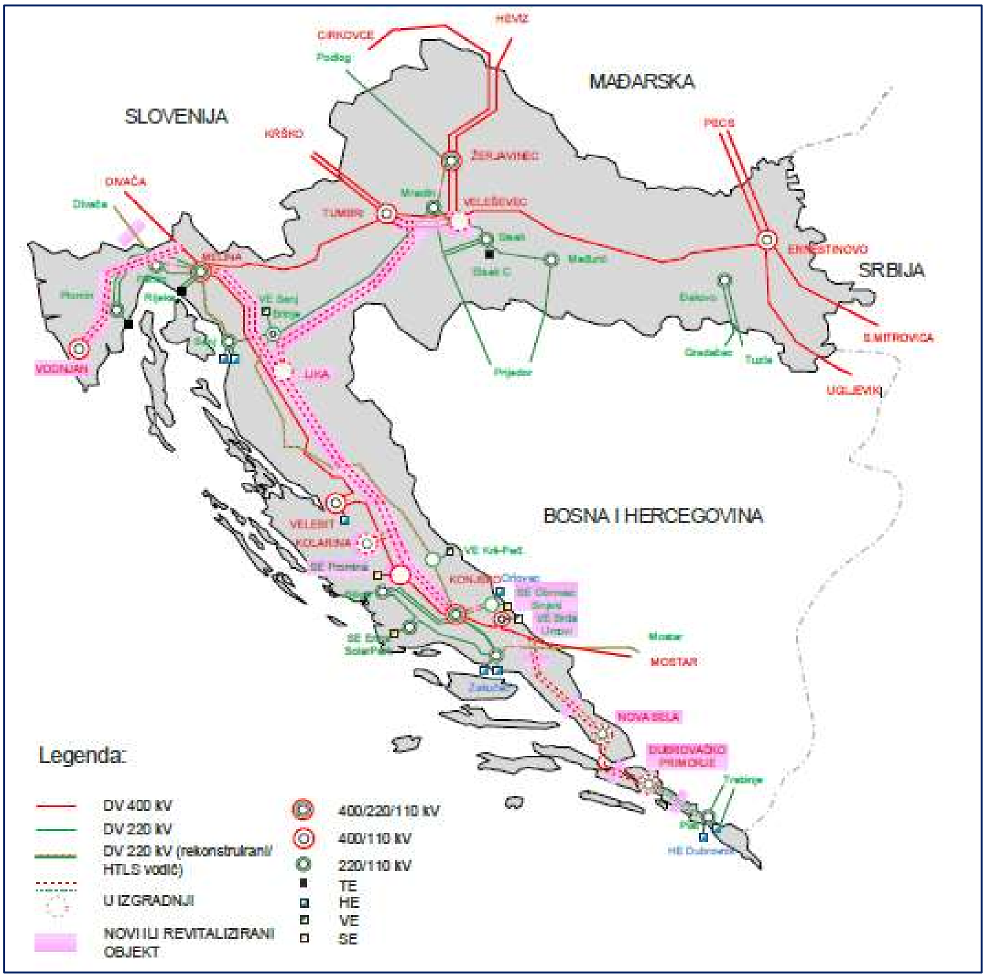

Figure 49 Schematic overview of the Croatian transmission network by the end of 2034 Source: Ten-Year Transmission Network Development Plan 2025–2034, HOPS

It is also important to note that, under the TEN-E Regulation (EU) 2022/869, the Republic of Croatia has defined non-binding targets for the development of offshore wind farms with a total capacity of 510 MW by 2030.

Croatian ports already play a significant economic and transport role, and their importance will further increase in the context of the energy transition. As natural interfaces between maritime and land transport, Croatian ports have the potential to become key hubs for the production, storage, and distribution of green hydrogen. Their geographical position, particularly that of the ports of Pula and Split, enables their integration into European energy and transport corridors, positioning them as essential nodes within the future hydrogen supply network. The development of port infrastructure, combined with planned investments in offshore renewable energy and the potential onshore production of green hydrogen, creates opportunities for ports to function as energy hubs, sites where hydrogen could be produced from local renewable resources while also supplying the maritime sector with clean fuels. At the same time, ports have the potential to serve as logistical nodes for hydrogen export to European markets, thereby expanding their role beyond traditional transport functions into strategic energy operations.

In this context, Croatian ports could follow the Italian model, where ports are increasingly integrated into the Trans-European Transport Network (TEN-T) and linked with initiatives such as the Italian Hydrogen Backbone. While in Italy the ports of Puglia and Veneto are already recognized as future hubs for green hydrogen transport and distribution, in Croatia, the ports of Pula and Split could assume a similar role — acting as regional centres capable of connecting local hydrogen production and distribution while also serving as international transport and energy nodes within the broader European hydrogen corridor system.

The pilot zone located in Istria County holds a significant advantage due to its well-developed existing energy infrastructure. In its immediate vicinity are the LNG terminal and pipelines transporting natural gas extracted from the northern Adriatic gas fields, as well as key nodes of the national electricity transmission network. The existence of this established gas pipeline system, which, in line with European recommendations, can be repurposed for hydrogen transport, represents a major strategic advantage for the region. In the future, it will facilitate the connection of green hydrogen projects both to the national grid and to cross-border systems. The Port of Pula and nearby industrial zones are natural locations for the development of logistical capacities, while the proximity of the Italian coast and the potential linkage with the Italian hydrogen network could open opportunities for cross-border cooperation and integration into the broader Mediterranean energy system. Furthermore, the surrounding industrial zones, as existing brownfield sites, are particularly suitable for future planning since they already occupy designated spatial areas, thereby eliminating the need to identify new sites within the already spatially constrained coastal zone, which is primarily designated for tourism and public use. The spatial plans of Istria County currently neither explicitly mention nor prohibit the development of offshore wind farms or the production of green hydrogen. At present, there are no designated zones specifically intended for the development of wind farms (Figures 5 and 6), while areas allocated for aquaculture are mainly located along the coastal belt, with no restrictions on conducting aquaculture activities within the pilot area. However, Istria County will soon face the closure of the Plomin 2 Thermal Power Plant, scheduled for 2033, which will create the need to replace coal-based electricity generation. As a response, plans foresee a shift toward solar and wind energy, with target installed capacities of 400 MW and 500 MW, respectively ((https://forbes.dnevnik.hr/aktualno/istra-priprema-teren-za-gradnju-pucinskih-vjetroelektrana-tri-su-potencijalne-zone/). In this context, linking new wind power plants with green hydrogen production could be technically simpler, as the required grid capacity already exists, meaning that necessary interventions and upgrades would be minimal. Consequently, it can be concluded that Istria County faces no major barriers regarding grid connection potential. Furthermore, an examination of protected areas under the Natura 2000 network (bioportal.hr) shows that the pilot area does not overlap with any Natura 2000 sites[6]. Therefore, spatial planning of the proposed zones is feasible, provided that all relevant environmental and nature protection regulations and policies are duly respected (Figure 50).

[6] For accurate and precise positioning of the pilot area, it is necessary to enter the coordinates into the GIS system on https://bioportal.hr/gis/

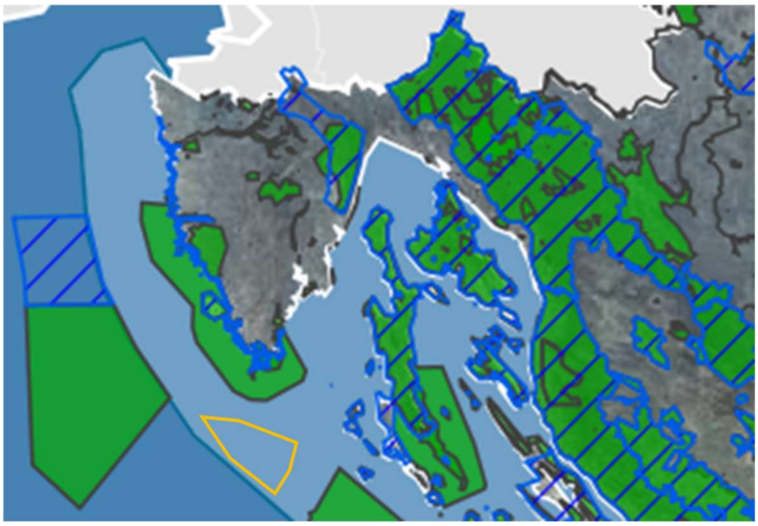

Figure 50 Location of the pilot area within the territorial sea of Istria County, marked in yellow; green areas represent Natura 2000 sites, modified after https://bioportal.hr/gis/

A review of nautical chart 100-16, Pula – Kvarner, shows that the pilot area within the territorial sea of Istria County is not located on a main maritime navigation route (https://www.hhi.hr/proizvodi-i-usluge/pomorske-navigacijske-karte/detalj/pmid/2639). However, to determine the exact and precise position, it is necessary to use the physical or printed chart and input the exact coordinates of the designated polygon (Figure 51).

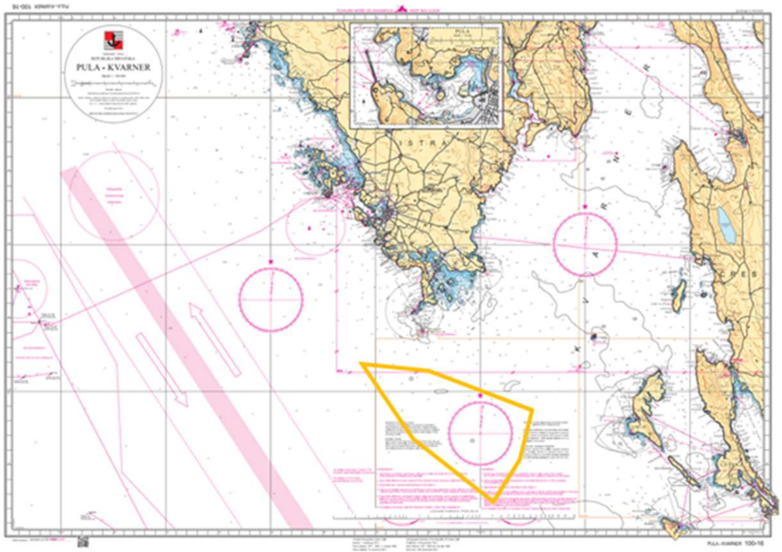

Figure 51 Location of the pilot area within the territorial sea of Istria County, marked in yellow, modified after https://www.hhi.hr/proizvodi-i-usluge/pomorske-navigacijske-karte/detalj/pmid/2639

In conclusion, given that the depth of the Adriatic Sea around the Istrian Peninsula is relatively shallow (up to approximately 50 meters), and that within this coastal zone there already exist offshore platforms for natural gas production, which, with the necessary modifications and permits, could be partially repurposed to accommodate central power units and electrolyzer installations, the area offers significant strategic advantages. In addition, there is existing connected infrastructure, including gas pipelines linking Croatia and Italy, as well as an established electricity transmission network with available capacity in the region, alongside plans for further grid reinforcement and expansion. Therefore, it can be concluded that this area currently represents the most favourable location in Croatia for the development of offshore wind farms and the production of green hydrogen.

Split-Dalmatia County also possesses significant potential due to its strong wind conditions and high solar radiation, making the area well-suited for the development of offshore wind farms and floating solar systems. The Port of Split, as the largest passenger and cargo port in Croatia, together with the industrial zone in Kaštela and the surrounding hinterland areas (which offer opportunities for brownfield investments), could become key locations for establishing centres dedicated to the production, storage, and distribution of green hydrogen. Regarding the two identified pilot areas within Split-Dalmatia County, which are designated for the generation of energy from renewable sources, an environmental assessment shows that they do not overlap or conflict with designated Natura 2000 [7] network sites, confirming their suitability for further spatial and technical planning (Figure 52) (https://bioportal.hr/gis/).

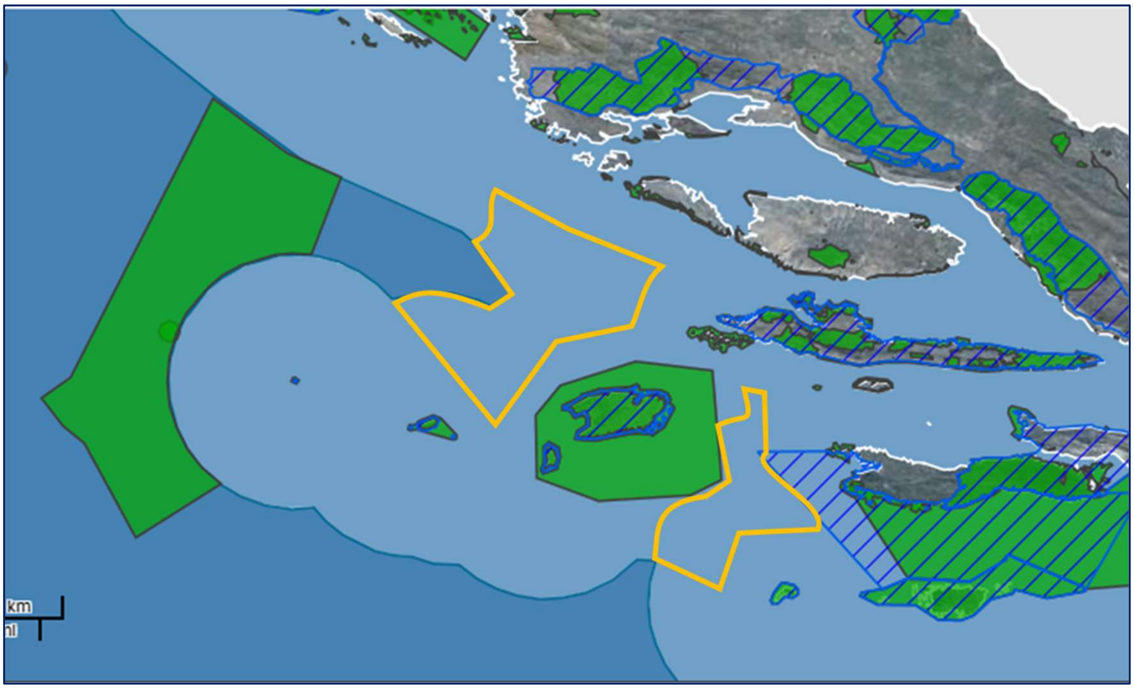

Figure 52 Location of the pilot area within the territorial sea of Split-Dalmatia County, marked in yellow; green areas represent Natura 2000 sites, modified after https://bioportal.hr/gis/

[7] For accurate and precise positioning of the pilot area, it is necessary to enter the coordinates into the GIS system on https://bioportal.hr/gis/

Examining the main navigation routes and based on the nautical chart INT 3412, Split – Gargano (https://www.hhi.hr/proizvodi-i-usluge/pomorske-navigacijske-karte/detalj/pmid/2556), the two pilot areas located within the territorial sea of Split-Dalmatia County are not situated on a main maritime navigation route. However, to determine the exact and precise location, it is necessary to use the physical (printed) chart and input the exact coordinates of the designated polygons[8] (Figure 53).

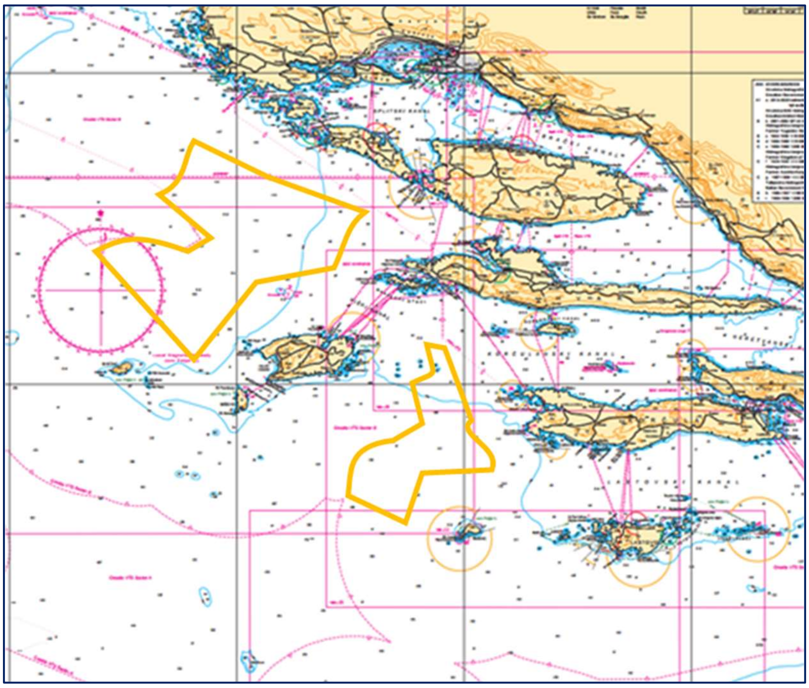

Figure 53 Location of the two pilot areas within the territorial sea of Split-Dalmatia County, marked in yellow, modified after https://www.hhi.hr/proizvodi-i-usluge/pomorske-navigacijske-karte/detalj/pmid/2556

In conclusion, the depth of the Adriatic Sea in the Split-Dalmatia County area ranges between 65 and 145 meters, and within this coastal zone there are already existing industrial areas, or *brownfield sites*, that could potentially be repurposed for new energy projects. The spatial plans of Split-Dalmatia County currently neither specify nor prohibit the development of offshore wind farms or the production of green hydrogen. At present, there are no designated zones for the development of wind farms (Figure 3 and Figure 4), while the areas allocated for aquaculture are located along the coastal belt, with no restrictions on conducting aquaculture activities within the pilot area.

Given these conditions, the proposed pilot zones could be effectively utilized for the installation of central power units and electrolyzers, providing a foundation for the integrated development of offshore renewable energy and green hydrogen production in the region. At the same time, the Split-Dalmatia County area has a well-developed electrical transmission network (Figure 48), with further upgrades and extensions already planned,

[8] For accurate and precise positioning of the pilot area, it is necessary to enter the coordinates into the nautical charts of the Croatian Hydrographic Institute.

and it is also included in the development plans of the transmission system operator Plinacro for the future hydrogen pipeline network (Figure 46). Therefore, it can be concluded that this region is currently suitable for the development of offshore wind farms and green hydrogen production.

Together, Istria County and Split-Dalmatia County represent two key hubs within Croatia's future hydrogen strategy: the northern Adriatic, with a focus on interconnections and cross-border energy flows, and the central Adriatic, emphasizing offshore renewable energy production and the development of port and industrial capacities (Figure 54). Unlike Italy, Croatia is only beginning to develop concrete pilot projects and does not yet have a dedicated hydrogen pipeline network. However, integration into European hydrogen corridors and the gradual repurposing of parts of the existing gas infrastructure are planned as long-term strategic solutions to support the national energy transition. This approach would enable the connection of domestic hydrogen production with international energy flows, while simultaneously stimulating the modernization of the electrical grid and the development of smart management systems necessary for the stable integration of new renewable energy capacities.

As in Italy, the integration of offshore wind farms and green hydrogen technologies in Croatia carries significant economic and social benefits. It can serve as a strong driver of industrial development, job creation, and reduction of dependence on fossil fuels, while also enhancing the sustainability and resilience of coastal communities. Through this process, Istria and Dalmatia can become testing grounds for innovative energy transition models, and Croatia gains the opportunity to position itself as a relevant partner in the development of the European network for renewable energy and green hydrogen.

	Istria County	Split-Dalmatia County
Development foundations	*Existing LNG terminal and gas pipelines from the northern Adriatic; existing electricity network nodes*	*Industrial zones (e.g., Kaštela, Split hinterland) as potential brownfield investments*
Hydrogen development phases	*Proximity of gas pipelines facilitates connection with national and cross-border networks*	*Planned integration with local industrial zones and port infrastructure*
Transmission network	*Advantage of repurposing existing gas pipelines and connection with Italy*	*Part of Plinacro's plans for the development of the future hydrogen pipeline*
Electric power grid	*Proximity to key network nodes; planned construction of a 400 kV grid in Istria*	*Well-developed grid; expansion and reinforcement planned for new RES capacities*
Renewable energy sources	*Replacement of Plomin with solar and wind power; green hydrogen production*	*Strong wind and solar potential; possible floating solar systems; green hydrogen*
Protected areas	*Pilot area not within Natura 2000 polygons*	*Proposed polygons not in conflict with Natura 2000*
Sea depth	*Relatively shallow depth (up to 50 m), suitable for fixed foundations*	*Depth 65–145 m, suitable for floating technologies*
Port infrastructure	*Port of Pula and nearby industrial zones as natural sites for logistics and distribution*	*Port of Split as the largest passenger and cargo port, with the Kaštela industrial zone*
Specific advantages	*Existing gas platforms could be repurposed for power units and electrolyzers*	*Larger pilot areas, not on main maritime routes; possible centralization of power units and electrolyzers*
Challenges	*Closure of Plomin 2 TPP requires new capacities and stable replacements*	*Sea depth, proximity of islands and nautical tourism; need for pipeline construction*
Role in the project	*The most favourable area in Croatia for offshore wind and hydrogen development due to existing infrastructure and shallow sea*	*Suitable area for floating wind and solar systems, with port and industrial capacities of Split*

Figure 54 A summary of the positive and negative sides of developing pilot areas in Croatia

3.10. Technology and Service Providers Analysis

The development of hydrogen technologies and their application within the energy transition require not only the availability of renewable energy sources but also a strong technological and industrial ecosystem. The analysis of technologies and service providers is essential for understanding the current market landscape, identifying existing capacities, and recognizing areas where additional support is needed. In the hydrogen sector, this encompasses a wide range of solutions, from production technologies such as different types of electrolyzers, through storage and transport systems, to end-use applications in industry, mobility, and the energy sector. Recognized service providers and technology companies play a vital role in implementing these solutions, as they enable knowledge transfer, plant maintenance, integration into existing energy systems, and the development of new business models. Special emphasis is placed on international cooperation and the role of European and national companies in the development of projects related to the production, distribution, and utilization of hydrogen (Figure 55).

Offshore wind farms can generate benefits beyond the energy sector, particularly within industries related to the manufacturing, assembly, and maintenance of complex engineering systems. This creates new demands for specialized knowledge and skills, from design and logistics to supervision, education, and safety, in which national universities and institutions could play an active role. Emphasis is placed on the contribution of experts in naval architecture, civil engineering, geophysics, geology, mechanical engineering, and electrical engineering, and both Italy and Croatia have a strong advantage in this regard, as they already possess these professional and academic resources.

For the shipbuilding industry, the development of offshore wind farms opens opportunities for the construction of specialized vessels with high added value, such as wind turbine installation vessels, jack-up units, supply ships, cable-laying vessels, or floating cranes. Although such products are currently manufactured primarily in developed economies, Croatian shipyards already possess experience in executing complex engineering projects. Notable examples include the self-elevating platform "Labin," built in the 1980s through joint production by the Uljanik, 3. Maj, Brodosplit, and Viktor Lenac shipyards, as well as a floating catamaran crane with a lifting capacity of 12,000 kN, which at the time was the largest of its kind in the world. The value of such vessels is several times higher than that of standard ships, making them highly attractive from an economic standpoint (Liščić et al., 2014).

Ports and port infrastructure play a crucial role in the development of the hydrogen economy, as they serve as key entry and exit points for the import, export, and domestic distribution of hydrogen and its derivatives. In the context of this project, the ports of Split and Pula are of particular importance in Croatia, while in Italy the strategic hubs include Venice, Ravenna, Manfredonia, and Bari. These ports represent potential energy hubs where capacities for the storage, handling, and distribution of hydrogen and its derivatives could be developed, alongside logistics centres for the installation and maintenance of offshore energy facilities. The importance of these ports also stems from their connection to European transport and energy corridors, making them well-suited for integration into the future European hydrogen supply network. Shipyards on both sides of the Adriatic, such as Uljanik and 3. Maj in Croatia, and Fincantieri in Italy, possess long-standing experience in the construction and overhaul of various types of vessels, placing them in a strong position to adapt to new requirements linked to the decarbonization of maritime transport. Their role may include the construction or conversion of vessels powered by hydrogen, ammonia, or other renewable-derived fuels, as well as the development of specialized ships for hydrogen transport and related logistics operations between offshore facilities and coastal terminals. This opens new markets and strengthens the competitiveness of the shipbuilding industries in both countries. It should be emphasized that Croatian shipyards possess the necessary production capacities (large workshops, cranes, heavy equipment, etc.) capable of meeting the technological requirements for manufacturing wind turbine components, both onshore and especially offshore, including towers, heavy nacelle castings, substructures for fixed turbines, and floating platforms for mobile units. Their strategic geographical position also makes them highly attractive, as a significant portion of finished products is transported by sea. To produce certain wind turbine components, Croatian shipyards could take advantage of governmental and EU incentives for renewable energy development. It is worth noting that the Brodosplit shipyard already has experience in manufacturing wind turbine towers for foreign companies developing onshore wind farms in Croatia. Conversely, the Croatian company Končar has developed its own 2.5 MW wind turbine, designed for onshore applications (Liščić et al., 2014).

Electricity system operators also play a crucial role in the integration of hydrogen technologies. In Croatia, this role is held by HOPS, and in Italy by TERNA. Their primary task is to ensure grid flexibility, balance between production and consumption, and enable the integration of hydrogen production from variable renewable sources such as wind and solar power. The development of green hydrogen projects — particularly offshore — will require close coordination with the electricity transmission systems of both countries, as well as the implementation of new connection and management models. Gas transmission operators, Plinacro in Croatia and SNAM in Italy, also face significant challenges and opportunities, as a gradual repurposing of existing gas pipelines for the transport of hydrogen or methane–hydrogen blends is anticipated. Italy is already planning the development of EHB (European Hydrogen Backbone) corridors across its territory, while Croatia, by connecting to these routes, could become an important transit hub. Achieving this will require detailed technical testing, material and infrastructure adaptation, and cross-border coordination between operators and regulatory bodies.

Certification bodies and standardization agencies in both countries also play an important role. Their task is to establish standards and certification schemes to produce green hydrogen, safety protocols, quality control, and the verification of emission reductions. This ensures market recognition and facilitates the integration of national capacities into the European and global hydrogen markets. In Croatia, this involves cooperation with both national and European standardization institutions, while Italy, as one of the EU's leading countries in the fields of energy and maritime transport, has an additional responsibility to align its certification practices with the European regulatory framework.

Sector	Croatia	Italy
Energy Operators	*HEP ODS, HEP OIE, HEP ESCO*	*Terna, Enel*
Gas Operators	*Plinacro (TSO)*	*Snam*
Industry / Consumption	*INA (Rafinerija Rijeka), Petrokemija Kutina, Nexe, Holcim, Cemex*	*ENI, Enel Green Power, Italcementi, Buzzi Unicem*
Port Authorities	*Rijeka, Ploče, Split, Zadar, Šibenik, Pula*	*Trst, Ravenna, Taranto, Brindisi, Bari*
Shipyards	*Viktor Lenac (Palumbo), 3. Maj, Brodosplit, Brodotrogir*	*Fincantieri / VARD*
Electrical Equipment and Cables	*KONČAR (D&ST, KET), Dalekovod, ELKA*	*Prysmian Group*
Engineering and Design	*IGH, Elektroprojekt, IVICOM, Ekonerg*	*Saipem, Rosetti Marino, Micoperi*
Institutes and Planning	*EI Hrvoje Požar, FER, FESB, RITEH*	*COP, Acciona, Renantis, BlueFloat, Politecnico di Milano, Univ. Bologna*
Certification and Safety	*RINA, DNV, Bureau Veritas, Lloyd's Register*	*RINA, DNV, BV, LR*
Logistics and Storage	*JANAF, LNG Hrvatska (Krk), Atlantska plovidba, Tankerska plovidba*	*Trevi Group, Grimaldi Group, GNV*
Electrolyzers and H_2 Technologies	*equipment import from EU, integration through EPC*	*Industrie De Nora (elektrode, gigafactory 2 GW/god), Enapter (Toscana) (AEM MW), MAIRE / NextChem (Power-to-X), Ansaldo Energia (H_2-ready turbine)*
RES Developers / EPC	*Encro, Professio Energia, RP Global, Ater Venture*	*ERG, Edison, A2A, Renantis, Renexia, Copenhagen Offshore Partners (COP) / Acciona Energía*
Heavy Industry and Steel	*Đuro Đaković Grupa*	*Tenaris Dalmine*
Financial Sector	*HBOR, EIB*	*CDP (Cassa Depositi e Prestiti), EIB*
Standardization and Policy	*HZN (Croatian normisation Department)*	*CEI (Comitato Elettrotecnico Italiano)*

Figure 55 Possible companies and services in the segment of offshore wind farms and green hydrogen production

4. Conclusion

The existing spatial plans, in which renewable energy sources and hydrogen are still rarely mentioned or limited to onshore projects, highlight the need for clearer strategic direction and alignment with European decarbonization goals. Both Italy and Croatia face similar challenges, particularly in harmonizing national energy planning with Maritime Spatial Planning (MSP) and recognizing the offshore wind and green hydrogen potential of the Adriatic Sea.

Considering regulatory and institutional framework, in Italy, the hydrogen sector is undergoing rapid development, yet still faces challenges such as fragmented regulation, lengthy permitting procedures, and uncertainties regarding the integration of hydrogen into existing gas networks. However, recent measures, including the simplification of authorization procedures for renewable hydrogen facilities and exemptions from grid fees for renewable electricity used in electrolysis, indicate gradual improvement of the regulatory framework. By extending measures like those applied for offshore wind projects up to 50 MW, Italy can further accelerate hydrogen deployment and attract new investments. Croatia, on the other hand, is still in the early stages of developing its national hydrogen strategy, which provides an opportunity for timely removal of regulatory barriers and strengthening institutional capacities. Parallel to the development of national infrastructure, it is essential to plan for cross-border energy integration, given the shared Adriatic space.

Furthermore, reflecting infrastructure and Pilot areas, both countries possess significant natural, infrastructural, and technical resources that enable the development of hybrid renewable and hydrogen projects. In Italy, a coordinated approach through the *Piano di Gestione dello Spazio Marittimo*, the *Strategia Nazionale Idrogeno*, and the planning frameworks of SNAM and Terna provides the foundation for accelerating the development of integrated infrastructure and strengthening energy independence. In Croatia, the existing gas corridors, electricity transmission network, and ports such as Pula and Split create a strong foundation for developing a sustainable model of green hydrogen production and distribution. The pilot areas in Istria and Dalmatia are particularly favourable, due to their proximity to industrial zones and *brownfield* sites, existing grid nodes, and shallow waters suitable for fixed or floating technologies.

Moreover, on the field of cooperation and European dimension, cooperation between Italy and Croatia under the INTERREG programme and similar cross-border initiatives will play a crucial role in aligning energy and hydrogen policies, facilitating knowledge exchange, and developing joint infrastructure projects. Through engagement in the *European Hydrogen Backbone* and the *Clean Hydrogen Partnership*, both countries can position the Adriatic Sea as a central hub for clean energy and innovation.

Finally, the integration of offshore wind power and green hydrogen technologies represents a new developmental paradigm in the energy transition of Italy and Croatia. Through coordinated action among national institutions, operators, research centres, and industry, significant progress can be achieved toward decarbonization, energy security, and the achievement of EU climate targets, while simultaneously strengthening regional resilience and promoting sustainable growth across the Adriatic region.

5. Literature:

Web Sources:

https://www.iea.org/reports/global-hydrogen-review-2022/executive-summary (International Energy Agency (IEA))

https://ehb.eu/

https://mpgi.gov.hr/vijesti-8/objava-javne-rasprave-o-prijedlogu-prostornog-plana-iskljucivog-gospodarskog-pojasa-u-jadranskom-moru/18685 (Croatian maritime spatial plan proposal for EEZ)

https://bioportal.hr/gis

Parker Hannifin Corporation. (n.d.). Hydrogen production and purification technologies. Retrieved from https://corpapps.parker.com/interactive-media/parker-hannifin-world/hydrogen-applications/production.html

H2ercules Initiative. (2024). H_2ercules project overview: accelerating hydrogen infrastructure in Europe. Retrieved from https://www.h2ercules.com/en

https://www.energy.gov/eere/fuelcells/hydrogen-storage

https://www.nrel.gov/news/detail/program/2024/offshore-wind-turbines-offer-path-for-clean-hydrogen-production

https://poshydon.com/en/home-en/

https://www.prnewswire.com/news-releases/dutch-state-joins-offshore-green-hydrogen-pilot-poshydon-via-ebn-302016835.html

https://www.crosswindhkn.nl/news/2025/04/offshore-solar-integration-with-offshore-wind-is-kicking-off-in-the-netherlands/

https://hydrogeneurope.eu/europes-first-offshore-h2-pilot-saw-electrolyser-performance-as-high-as-on-land/

https://www.lhyfe.com/press/lhyfe-reviews-the-results-of-the-sealhyfe-project-the-worlds-first-offshore-hydrogen-production-pilot-objectives-met-and-progression-to-an-unprecedented-level-of-operational-excellence/

https://hope-h2.eu/#project

https://oysterh2.eu/

https://www.rwe.com/en/press/rwe-renewables/2022-02-15-rwe-and-neptune-energy-join-forces-to-accelerate-green-hydrogen-production-in-dutch-north-sea

https://www.rwe.com/en/research-and-development/hydrogen-projects/h2opzee/

https://www.infobuildenergia.it/approfondimenti/eolico-offshore-italia-idrogeno

https://www.sid.mit.gov.it/documenti-piano

https://ultfarms.eu/about/

https://www.norther.be/offshore_seaweed_farm/

https://ultfarms.eu/fino3-summer-update/
https://ultfarms.eu/samso-pilot-update-may-2024/
https://interregvlaned.eu/wier-wind/over-ons
https://www.nordicinnovation.org/news/high-potential-co-location-offshore-wind-and-fish-farming
https://www.nordicinnovation.org/programs/offwoff-co-location-project
https://owcltd.com/media/news/aquawind-project-breakthrough-prototype-launch-complete/
https://www.newsgd.com/node_e9dced8600/5a39cfd85b.shtml
https://ehb.eu/newsitem/european-hydrogen-backbone-grows-to-meet-repowereu-s-2030-hydrogen-targets
https://ehb.eu/page/country-specific-developments
https://www.hydrogeninsight.com/innovation/german-gas-operator-says-20-hydrogen-blending-trial-in-100-homes-has-been-100-trouble-free-after-six-months/2-1-1455488?utm
https://www.south2corridor.net/?utm_source
https://www.rinnovabili.net/tech-innovations-and-startups/energy-tech-innovations-and-startups/hydrogen-gas-blend-italy-launches-5-test-in-gas-network/?utm
https://www.reuters.com/business/energy/italgas-edison-test-green-hydrogen-an-industrial-plant-2025-05-15/?utm
2024-2028 Industrial Plan update (TERNA)
https://www.geni.org/globalenergy/library/national_energy_grid/italy/italiannationalelectricitygrid.shtml
https://ehb.eu/page/country-specific-developments?utm_source=chatgpt.com#croatia-plinacro
https://www.hera.hr/hr/docs/2025/Prijedlog_2025-08-01_1.pdf
https://forbes.dnevnik.hr/aktualno/istra-priprema-teren-za-gradnju-pucinskih-vjetroelektrana-tri-su-potencijalne-zone/
https://www.hhi.hr/proizvodi-i-usluge/pomorske-navigacijske-karte/detalj/pmid/2639
https://www.hhi.hr/proizvodi-i-usluge/pomorske-navigacijske-karte/detalj/pmid/2556

EU regulative and legislative documents:

European Commission, (2021), European Green Deal: Communication COM (2019) 640 Final, Brussels

European Commission, (2020), Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions, A hydrogen strategy for a climate-neutral Europe, Brussels

European Parliament, (2020), European Strategy for Hydrogen, 2020/2242(INI), Brussels https://oeil.secure.europarl.europa.eu/oeil/en/procedure-file?reference=2020/2242(INI)

European Commission, (2023), Fit for 55 Package – Delivering the EU's 2030 Climate Target on the way to Climate Neutrality, Brussels

European Parliament and Council, (2014), Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning, Document 32014L0089, Brussels http://data.europa.eu/eli/dir/2014/89/oj

European Parliament and Council, (2018), Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance.), Document 32018L2001, Brussels http://data.europa.eu/eli/dir/2018/2001/oj

European Parliament and Council, (2022), Regulation (EU) 2022/869 of the European Parliament and of the Council of 30 May 2022 on guidelines for trans-European energy infrastructure, amending Regulations (EC) No 715/2009, (EU) 2019/942 and (EU) 2019/943 and Directives 2009/73/EC and (EU) 2019/944, and repealing Regulation (EU) No 347/201 (Guidelines for trans-European energy infrastructure, Document 32022R0869), Brussels http://data.europa.eu/eli/reg/2022/869/oj

European Parliament and Council, (2023a), Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin, Document 32023R1184, Brussels http://data.europa.eu/eli/reg_del/2023/1184/oj

European Parliament and Council, (2023b), Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU (Text with EEA relevance), Document 32023R1804, Brussels http://data.europa.eu/eli/reg/2023/1804/oj

European Parliament and Council, (2023c), Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (Text with EEA relevance, Document 32023R1805, Brussels http://data.europa.eu/eli/reg/2023/1805/oj

European Parliament and Council, (2023d), Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation) (Text with EEA relevance), Document 32023R2405, Brussels http://data.europa.eu/eli/reg/2023/2405/oj

European Parliament and Council, (2023e), Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652, Document 32023L2413, Brussels http://data.europa.eu/eli/dir/2023/2413/oj

European Parliament and Council, (2024a), Directive (EU) 2024/1788 of the European Parliament and of the Council of 13 June 2024 on common rules for the internal markets for renewable gas, natural gas and hydrogen, amending

Directive (EU) 2023/1791 and repealing Directive 2009/73/EC (recast) (Text with EEA relevance), Document 32024L1788, Brussels http://data.europa.eu/eli/dir/2024/1788/oj

European Parliament and Council, (2024b), Regulation (EU) 2024/1789 of the European Parliament and of the Council of 13 June 2024 on the internal markets for renewable gas, natural gas and hydrogen, amending Regulations (EU) No 1227/2011, (EU) 2017/1938, (EU) 2019/942 and (EU) 2022/869 and Decision (EU) 2017/684 and repealing Regulation (EC) No 715/2009 (recast) (Text with EEA relevance), Document 32024R1789, Brussels http://data.europa.eu/eli/reg/2024/1789/oj

Italian National Framework, Strategies, Plans:

Governo della Repubblica Italiana, (2017), Decreto Legislativo 16 dicembre 2016, n. 257, Disciplina di attuazione della direttiva 2014/94/UE sulla realizzazione di infrastrutture per combustibili alternativi, Gazzetta Ufficiale, Serie Generale n. 10 del 13 gennaio 2017 – Suppl. Ordinario n. 3, Roma. Availabe: https://www.gazzettaufficiale.it/eli/id/2017/01/13/17G00005/sg

Governo della Repubblica Italiana, (2021), Decreto Legislativo 8 novembre 2021, n. 199, Attuazione della direttiva (UE) 2018/2001 sulla promozione dell'uso dell'energia da fonti rinnovabili, Gazzetta Ufficiale, Serie Generale n. 285 del 30 novembre 2021 – Suppl. Ordinario n. 42., Roma. Available:

https://www.gse.it/normativa_site/GSE%20Documenti%20normativa/ITALIA_DLGS_n199__08_11_2021.pdf

Governo della Repubblica Italiana, (2021), Piano Nazionale di Ripresa e Resilienza, Roma

Governo della Repubblica Italiana, (2023), Decreto-Legge 24 febbraio 2023, n. 13, Disposizioni urgenti per l'attuazione del Governo della Repubblica Italiana, Piano nazionale di ripresa e resilienza (PNRR) e del Piano nazionale degli investimenti complementari al PNRR (PNC*)*, Gazzetta Ufficiale, Serie Generale n. 47 del 24 febbraio 2023., Roma, Available: https://www.gazzettaufficiale.it/eli/id/2023/02/24/23G00022/sg

Ministero dell'Ambiente e della Sicurezza Energetica (MASE), (2019), Piano nazionale integrato per l'energia e il clima (PNIEC, eng. National Integrated Plan for Energy and Climate), Roma. link

Ministero dell'Ambiente e della Sicurezza Energetica (MASE), (2022), Strategia Nazionale per l'Idrogeno – Linee Guida Preliminari*.* Roma, link

Ministero dell'Ambiente / Ministero delle Infrastrutture e della Mobilità Sostenibile, (2024), Piano di gestione dello spazio marittimo italiano – Area marittima Adriatico, Decreto Ministeriale, DM 2023-000035). Roma. Available: https://va.mite.gov.it/it-IT/Oggetti/Documentazione/8338/12277

Ministero dell'Ambiente e della Sicurezza Energetica (MASE), (2024), Strategia Nazionale Idrogeno – Novembre 2024, Roma, Availble: https://www.mase.gov.it/portale/documents/d/guest/strategia-nazionale-idrogeno-pdf

Ministero dell'Interno, (2018), Decreto del Ministero dell'Interno 23 ottobre 2018, Regola tecnica di prevenzione incendi per la progettazione, costruzione ed esercizio degli impianti di distribuzione di idrogeno per autotrazione (18A07049), 2018, Gazzetta Ufficiale, Serie Generale n. 257 del 5 novembre 2018, Roma. Available:

https://www.gazzettaufficiale.it/eli/id/2018/11/05/18A07049/SG

Presidenza del Consiglio dei Ministri, (2017), Decreto: Linee Guida per la Pianificazione dello Spazio Marittimo, Decree of 1 December 2017, Gazzetta Ufficiale No. 19/2018, Roma

Italian Ministry of Infrastructure and Transport, (2018), Piano di gestione dello spazio marittimo Italiano [Decree of the Presidency of the Council of Ministers, 1 December 2017], Roma

SNAM, (2021a), Snam 2030 vision and 2021-2025 plan, pp.45, available at: https://www.snam.it/en/investor-relations/strategy/2023-27-Strategic-Plan.html

SNAM, (2021b), Sustainable finance framework 2021, pp. 40

TERNA, (2024), Industrial Plan Update 2025-2028, Empowering Tomorrow, pp.48, available at: https://www.terna.it/en/media/news-events/detail/2024-2028-industrial-plan-update

Croatian National Framework, Strategies, Plans, Legislative:

EKONERG – institut za energetiku i zaštitu okoliša, (2021), Scenarij za postizanje klimatske neutralnosti u Republici Hrvatskoj do 2050. godine, Ministarstvo gospodarstva i održivog razvoja, Zagreb. link

Hrvatski operator prijenosnog sustava (HOPS), 2024, Desetogodišnji plan razvoja prijenosne mreže 2025.–2034., Zagreb.

Hrvatski Sabor, (2019), Pomorski zakonik Republike Hrvatske, 2019, Zagreb, Narodne novine 181/04, 76/07, 146/08, 61/11, 56/13, 26/15, 17/19, link

Hrvatski Sabor, (2025), Zakon o kritičnoj infrastrukturi, 2025, Zagreb, Narodne novine 89/2025, link

Javna ustanova RERA S.D. za koordinaciju i razvoj Splitsko-dalmatinske županije, (2022), Provedbeni program Splitsko-dalmatinske županije za razdoblje 2022.-2025, Split, link

Plinacro d.o.o., (2023), Desetogodišnji plan razvoja plinskog transportnog sustava Republike Hrvatske (TYNDP 2023–2032). Zagreb

Vlada Republike Hrvatske, (2020), Strategija energetskog razvoja Republike Hrvatske do 2030. s pogledom na 2050. godinu, Narodne novine, br. 25/2020, Zagreb, Available:

https://narodne-novine.nn.hr/clanci/sluzbeni/2020_03_25_602.html

Vlada Republike Hrvatske, (2021a), Nacionalni plan oporavka i otpornosti 2021.–2026. Zagreb. Available: https://planoporavka.gov.hr/

Vlada Republike Hrvatske, (2021b), Strategija niskougljičnog razvoja Republike Hrvatske do 2030., s pogledom na 2050. Narodne novine, br. 63/2021, Zagreb. Available:

https://narodne-novine.nn.hr/clanci/sluzbeni/2021_06_63_1205.html

Vlada Republike Hrvatske, (2022), Hrvatska strategija za vodik do 2050. Narodne novine, br. 40/2022, Zagreb. Available: https://narodne-novine.nn.hr/clanci/sluzbeni/2022_03_40_492.html

Vlada Republike Hrvatske, (2025), Revidirani Integrirani nacionalni energetski i klimatski plan Republike Hrvatske za razdoblje od 2021. do 2030. (NECP). Zagreb, Ministarstvo gospodarstva i održivog razvoja.

Available:
https://mingo.gov.hr/UserDocsImages/UPRAVA%20ZA%20ENERGETIKU/NECP_Update_HRV_HR_Revidirani.pdf

Technical and Academic Sources:

Belamarić, B. and Bošnjak, R., (2023), Plan razvoja plinske infrastrukture i mogućnosti primjene vodika u Hrvatskoj. Nafta i Plin, Vol. 43., No. 178.-179.

Chico Moreno, F. D., (1990), Design of an Electrolyzer Integrated in an Offshore Wind Turbine System, EngD Thesis, University of Twente, Bogota, Columbia

Dukku, H. B., Arnaut, J., Johnstone, C., Riccardi, A. and Ordonez Sanchez, S., (2025), Techno-Economic Feasibility Study of Hydrogen Transportation in Greenland Using Pipeline and Maritime Routes. J. Ocean Eng. Technol. February 2025; 39(1), pp. 122-132.https://doi.org/10.26748/KSOE.2024.088

Fang, R. (2019). Life cycle cost assessment of wind power–hydrogen coupled integrated energy system. International Journal of Hydrogen Energy, Volume 44, Issue 56, p. 29399-29408. https://doi.org/10.1016/j.ijhydene.2019.03.192

Freja Offshore, SubFarm, DHI, ÅKP Fyrbodal's Association of Local Authorities, (2025), Nordic Innovation, Co-locating Floating Wind and Aquaculture: Lessons from the Nordic OFFWOFF Project, OFFWOFF Project by Nordic Innovation. https://www.nordicinnovation.org/2025/co-locating-floating-wind-and-aquaculture

Gandiglio, M. and Marocco, P., (2024), Mapping Hydrogen Initiatives in Italy: An Overview of Funding and Projects, Energies 2024, 17, 2614, https://doi.org/10.3390/en17112614

Gao, X., Chen, Y. et Wang, Y., (2024). Next-Generation Green Hydrogen: Progress and Perspective from Electricity, Catalyst to Electrolyte in Electrocatalytic Water Splitting. Nano-Micro Lett. 16, 237 https://doi.org/10.1007/s40820-024-01424-2

Ghaebi Panah, P., Cui, X., Bornapour, M., Hooshmand, R. A., & Guerrero, J. M. (2022). Marketability analysis of green hydrogen production in Denmark: Scale-up effects on grid-connected electrolysis. International Journal of Hydrogen Energy, 47(25), 12443-12455. https://doi.org/10.1016/j.ijhydene.2022.01.254

Koornneef, J., (2021), Unlocking potential of the North Sea, North Sea Energy & PosHYdon, International Conference on Maritime Hydrogen and Marine Energy, https://north-sea-energy.eu

Krol, A., Gajec, M., Holewa-Rataj, J., Kukulska-Zając, E. et Rataj, M., (2024). Hydrogen Purification Technologies in the Context of Its Utilization, Energies 2024, 17(15), 3794 ; https://doi.org/10.3390/en17153794 (This article belongs to the Special Issue Advances in Hydrogen Energy IV)

Lambert, M. and Schulte, S., (2021), Contrasting European hydrogen pathways: An analysis of differing approaches in key markets, Oxford Institute for Energy Studies and Institute of Energy Economics at the University of Cologne, OIES paper: NG 166

Li, Y., Zhou, S. et Pan, G. (2023). An Effective Optimisation Method for Coupled Wind–Hydrogen Power Generation Systems Considering Scalability. Processes 2023, 11(2), 343. https://doi.org/10.3390/pr11020343

Lipiäinen, S., Lipiäinen, K., Ahola, A. and Vakkilainen, E., (2023), Use of existing gas infrastructure in European hydrogen economy. International Journal of Hydrogen Energy, Volume 48, Issue 80, pp. 31317-31329 https://doi.org/10.1016/j.ijhydene.2023.04.283

Liščić, B., Senjanović, I., Čorić,V., Kozmar, H., Tomić, M. and Hadžić, N., (2014), Off shore Wind Power Plant in the Adriatic Sea: An Opportunity for the Croatian Economy. Transactions on maritime science, V3, No2, pp. 103-110., doi: 10.7225/toms.v03.n02.001

Maar, M., Holbach, A., and Boderskov, T., (2023), Multi-use of offshore wind farms with low-trophic aquaculture can help achieve global sustainability goals. Commun Earth Environ 4, 447. https://doi.org/10.1038/s43247-023-01116-6 https://www.nature.com/articles/s43247-023-01116-6

Miranda, F., Rosa-Santos, P., Taveira-Pinto, F., Guan, D., and Fazeres-Ferradosa, T., (2025), Aquaculture and offshore wind: A review of co-location design challenges, Ocean Engineering 318 (2025) 120161, https://www.sciencedirect.com/science/article/pii/S0029801824034991?via%3Dihub

Moultak, M, Fichter, T., Peterse, J., Cantor, Konstantinos J., Jan Cihlar, K., Schimmel, M. and Overgaag, M., (2023), Assessing the benefits of a pan-European hydrogen transmission network, Gas for Cllimate & Guidehouse, Nedherlands

Slowinski, R., Sagdur, Y., van Rossum, R., Kozub, A., Overgaag, M., Amazo Blanco, A., Michelet, A., Ho, G., Kandathiparambil, S. and London, P., (2023), European Hydrogen Backbone, Implementation roadmap —cross border projects and costs update, Amber Grid, Bulgartransgaz, Conexus, CREOS, DESFA, Elering, Enagás, Energinet, Eustream, FGSZ, FluxSwiss, Fluxys Belgium, Gas Connect Austria, Gasgrid Finland, Gassco, Gasunie, GASCADE, Gas Networks Ireland, GRTgaz, National Gas Transmission, NET4GAS, Nordion Energi, OGE, ONTRAS, Plinacro, Plinovodi, REN, Snam, TAG, Teréga, Transgaz, Transitgas AG and the TSO of UA, Guidehouse, Netherlands, pp. 41

van Rossum, R., Jens, J., La Guardia, G, Wang, A., Kühenen, L. and Overgaag, M., (2022), European Hydrogen Backbone, A European hydrogen infrastructure vision covering 28 countries, April 2022, Amber Grid, Bulgartransgaz, Conexus, CREOS, DESFA, Elering, Enagás, Energinet, Eustream, FGSZ, FluxSwiss, Fluxys Belgium, Gas Connect Austria, Gasgrid Finland, Gassco, Gasunie, Gas Networks Ireland, GAZ-SYSTEM, GRTgaz, National Grid, NET4GAS, Nordion Energi, OGE, ONTRAS, Plinacro, Plinovodi, REN, Snam, TAG, Teréga, and Tranzitgas, Guidehouse, Netherlands

Venugopalan, S., Navarro, J. G. and Buijs, L, (2024), State of Art in Offshore Hydrogen Production, TNO Public, TNO 2024 P11648, Project number 060.58216, pp 55., Energy & Materials Transition, Netherlands

Regional and Project-Based Sources:

Interreg Italy–Croatia Programme (2025). *Joint Planning for Offshore Renewable Integration in the Adriatic – Project Documentation.*

Online Data and Mapping Tools:

European Hydrogen Backbone (EHB) Map Viewer (2024): https://ehb.eu

Bioportal (2024). Natura 2000 Viewer – Republika Hrvatska. Available at: https://bioportal.hr/gis

GIS Viewer for Maritime Spatial Planning Italy (MASE, 2024): https://mase.gov.it/pianificazione-marittima

Hrvatski hidrografski institut (HHI). Nautical Chart Catalogue (Nautičke karte 100-16 (Pula–Kvarner) i INT 3412 (Split–Gargano)). Available at: https://www.hhi.hr