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ADVANCED REVIEW

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Technical and economic challenges for floating offshore wind deployment in Italy and in the Mediterranean Sea

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Abstract

Offshore wind is nowadays already well developed in the North European countries. Ninety-nine percent of the offshore wind turbines are installed on fixed foundations in shallow waters. For areas with water depth greater than 50–60 m, the floating wind is the cheapest and mostly used technology. This technology is going to reach the commercial phase in a few years, thus disclosing the potential of all marine areas with deep waters close to the coast, including the Mediterranean basin. One of the main challenges for floating offshore wind deployment in this area is the achievement of its economic feasibility. The offshore wind resource in the Mediterranean is generally lower than the one in the North Sea and in Oceans and the cost of offshore wind farms, especially with floating technology, is higher than the present offshore wind farm installations also because this industrial sector has not yet started in this area. However, in the Mediterranean area, the potential of offshore wind to contribute to the decarbonization pathway and reduce the dependence on imported fuel supply is substantial. Numerous studies, examined in this article, have already performed a technical-economic assessment of offshore wind farms in different countries and geographical areas within the basin. A significant number of offshore wind projects are already in different stages of development, confirming the industrial interest and readiness of the Mediterranean offshore wind energy sector. The article provides a comprehensive review of various factors influencing the future deployment of offshore wind in the Mediterranean.

It covers a range of topics including technology advancements, resource assessment, wind energy potential, ongoing projects, costs, and economic aspects. Additionally, it discusses environmental sustainability, regulatory frameworks, supply chain logistics, and system integration. The updated review presented in this article could assist decision-makers and stakeholders in gaining a better understanding of the characteristics of this promising sector and accelerating its development.

This article is categorized under:
Sustainable Energy > Wind Energy

KEYWORDS

floating offshore wind, Italy, LCOE, Mediterranean, NPV, offshore wind

1 | INTRODUCTION

Since the first decade of the 2000s, when the offshore wind sector began to experience significant growth in the North Sea, pioneering studies (Bard, 2010; Botta et al., 2009; Gaudiosi & Borri, 2010) assessed the offshore wind potential of Italy and Mediterranean Sea. However, for many years this area was perceived as a secondary market for offshore wind, relatively small and challenging to develop. The wind resource is, on average, lower than that of the North Sea, and the water depth increases rapidly close to the coast. Consequently, most of the Mediterranean offshore wind energy potential will be harnessed using floating technology because wind turbines on fixed foundations (typically monopiles and jackets) can only be installed in the water depths lower than 50–60 m (Barter et al., 2020; WindEurope, 2017). The deployment of wind floating systems began in the Mediterranean with the introduction of small-scale prototypes, such as the 80 kW turbine by BlueH (https://www.bluehengineering.com/historical-development.html), followed by larger demonstrators like the 2.3 MW Hywind in Norway (Ibrion & Nejad, 2023) and the 2 MW WindFloat in Portugal (Roddier et al., 2010). Presently, pre-commercial floating wind arrays have been installed in Scotland and Portugal. The Hywind Scotland project features five 6 MW wind turbines, while Windfloat Atlantic in Portugal has five 5 MW turbines (Edwards et al., 2023; European Commission, 2022). Confidence in floating wind technology is on the rise. In the Mediterranean, three pilot projects in France have already been authorized, and there is a significant number of floating wind projects proposed in Italy. According to the European Wind Energy Association, WindEurope, the European Commission expects 10 GW of floating wind capacity (WindEurope, 2023) to be installed in Europe by 2030. Beyond resource and technology, the Mediterranean Sea is a very crowded basin with many existing offshore activities, including fishing, shipping, mining, and military areas. It also boasts a robust tourist industry along its coasts (Westerberg et al., 2015) and has unique environmental features such as the Posidonia beds and the Marine Mammal Sanctuary (Boero et al., 2016). Furthermore, more than 20 countries from three continents border the Mediterranean, each with different cultural, geopolitical, and legal-regulatory aspects. Nevertheless, in recent years, other factors concurred to accelerate the disclosure of the Mediterranean offshore wind energy sector. These factors include an increased awareness of the environmental and economic benefits of transitioning to a decarbonized energy system (IEA, 2021; WindEurope, 2019) and, after the 2021 war, a recognition of the potential that renewable energy production offers for enhancing the security of energy supply (IEA, 2022; Mišík, 2022). Other aspects are related to the presence of existing infrastructure in many countries facing the Mediterranean Sea, already engaged in offshore sector. These infrastructures could be re-designed and adapted for the offshore wind sector, contributing to the potential creation of local jobs and boosting the local economy (Crown Estate Scotland, 2018; Serri, 2018). Among the Mediterranean countries, Italy holds a very favorable position at the center of the basin, boasting more than 8000 km of coast, numerous shipyards and ports, and the first offshore Mediterranean wind farm operating in Taranto harbor, 30 MW Beleolico wind farm on fixed foundations (Severini et al., 2023). Additionally, there have been numerous requests for offshore wind connections to the power grid, exceeding 90 GW of capacity by the end of 2023 (https://www.terna.it/en/electric-system/grid/econnextion). Italy is recognised as one of the five future floating offshore wind market snapshots analyzed in a recent global study (GWEC, 2022). Short-term deployments are also expected in France and Greece. The offshore wind sector in other Mediterranean countries holds great promise, with many ongoing studies and announced developments at various time scenarios, reported in detail in the next sections.

Two main open questions persist regarding the deployment of offshore wind energy in the Mediterranean area: Is floating technology mature? What will be the energy costs? The aim of this paper is to provide an advanced review of the studies on these two main topics, offering updated information to sector stakeholders and policymakers. Two main sections have been developed: Section 2 which focuses on technology, including resource assessment, and Section 3 which delves into costs. Section 4 is dedicated to brief analysis of other aspects that could affect the offshore wind energy sector and market, such as environmental sustainability, policy framework, system integration, and supply chain.

The ambitious intent of this article is to present the state-of-the-art knowledge in this multidisciplinary sector and identify the main research gaps and potential that can help overcome the current technological and economic barriers to the adoption of offshore wind in the Mediterranean market.

2 | TECHNOLOGIES, RESOURCE ASSESSMENT, POTENTIAL AND PROJECTS

2.1 | Technology overview

2.1.1 | Wind turbine

Wind turbines can be broadly classified into two main categories based on their axis orientation: Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT) (Das et al., 2017; www.deepwind.eu/). Although some vertical axis floating wind turbines have been analyzed (Arredondo-Galeana & Brennan, 2021; Huijs et al., 2018; Micallef, 2023; Sukanta et al., 2017) and are in demonstration phase (https://seatwirl.com/products/), most floating wind turbines in studies and demonstrations are HAWT. Among them, there are some studies about the use of two blades and/or downwind wind turbines (Pao et al., 2021; Schütt et al., 2020). Another difference in offshore wind turbines comes from the drivetrain typology. Both geared and direct-drive generator systems are being considered. In Nejad et al. (2022) and in Ayub et al. (2023), numerous advantages and constraints for each drivetrain type are outlined, along with a description of the required components. Most of the generators in new offshore wind turbines are based on Permanent Magnet Synchronous Generators (PMSG). As of today, according to GWEC (2022), the two primary drivetrain technologies in Europe are the Direct Drive turbine Permanent Magnet Synchronous Generators (DD PMSG) and the Medium-Speed turbine with a PMSG (MS PMSG). In 2021, these technologies held almost equal market shares. PM drivetrains enable a reduction in the occupied space within the nacelle, resulting in a decrease in installation constraints. These motors possess very low rotor inertia, which, when combined with very high starting torque, allows for extremely swift and continuous micro-adjustment of blade pitching and nacelle yawing (GWEC, 2022).

2.1.2 | Foundations

Offshore wind energy technology is categorized into two main classes based on the type of support for the wind turbine: fixed foundations and floating platforms. An illustration of the main concepts for fixed and floating platforms is depicted in Figure 1.

Regarding fixed foundations, various technologies have been developed based on weather and sea conditions, as well as seabed types. The main types include: gravity and monopile foundations (Mathern et al., 2021), tripod and jacket foundations (for transitional water depths of 30–60 m).

Currently, fixed foundation is the most widely used technology worldwide. China holds the record for the largest offshore operational turbine (My-SE16-260, with 16 MW on a jacket platform) and the highest total installed offshore capacity, followed by Germany, United Kingdom, Netherlands, the United States, and so forth (GWEC, 2022). However, at depths around 50–60 m, it becomes technically and economically challenging to install fixed foundation (Castro-Santos et al., 2016; European Commission, 2020a; Musial et al., 2016; Myhr et al., 2014). As we move further from the coast, especially in the Mediterranean basin, sea depth increases, necessitating the installation of floating offshore wind turbines (Díaz et al., 2022).

FIGURE 1 Offshore wind fixed and floating sub-structures. *Source*: Illustration by Josh Bauer/NREL.

Floating offshore wind technology is still in the pre-commercial stage and a consensus on the platform design has not yet been reached, although processes to evaluate the best floating platform for each location are being widely explored (Alkhalidi et al., 2023). This technology has been adapted from the oil and gas industry sector (Barooni et al., 2023; Sykes et al., 2023; Wu et al., 2023), where is already proven, with lesson learned over the years (Sykes et al., 2023). Due to the importance of stabilization, platforms are often categorized into four main types, dependent on the method by which they achieve stability (Edwards et al., 2023; Ghigo et al., 2020):

Spar platform: a steel or concrete cylindrical structure ballast-stabilized with water or solid component (Ghigo et al., 2020), that relies on buoyancy and has a small waterplane area (Santhakumar et al., 2022). Proper design of the ballast allows it to counteract pitch movements caused by tidal, wave and wind, thereby enhancing its stability (Barooni et al., 2023; Edwards et al., 2023). Mooring lines are utilized to prevent drifting and limit the surge and sway motions (Barooni et al., 2023) (Weight for 6 MW: ~3500 t; GWEC, 2022).

Tension leg platform (TLP): is a floating platform with a submerged buoyancy tank tethered to the seabed by vertical tendons which counteract the motion caused by waves and wind on the platform guaranteeing the static stability (GWEC, 2022) (Weight for 6 MW: ~2000 t; GWEC, 2022).

Semisubmersible (SEMI-SUB): the general structure is comprised of three or more columns interconnected by submerged pontoons or cross braces and heave plates to increase hydrostatic stability and buoyancy (Barooni et al., 2023; Díaz et al., 2022; Sykes et al., 2023). WindFloat is the most known design with three columns and active ballast compensation (Roddier et al., 2010). Other configurations have been studied for semisubmersible platform with a different number of columns (Ghigo et al., 2020) or different design of the platform, (Ferri et al., 2020). Another approach considers the installation of two turbines on the same platform (www.twinhub.co.uk/) or structure with only one mooring point (Maximiano et al., 2021). Most of these configurations are designed for steel realization; however, examples of concrete platform have already been tested (Iberdrola to develop two floating offshore wind demonstration projects) (Weight for 6 MW: ~3000 t—steel; GWEC).

Barge: This type of platform is characterized by a large waterplane area which achieve the overall stability (Barooni et al., 2023). A common barge design is Ideol. This platform has been used in the first floating offshore wind

France's installation off the coast of Le Croisic mounting a turbine of 2 MW. This concept is distinguished by a rectangular annulated-shaped floating substructure with a pool at its center named moonpool that suppress wave induced loading (Barooni et al., 2023; Santhakumar et al., 2022) (Weight for 6 MW: 2000 t ÷ 8000 t depending on materials; GWEC).

2.1.3 | Mooring and anchoring system

The mooring system of a floating wind turbine establishes the mechanical link between the floating substructure and the seabed. Its configuration hinges on various factors, contingent on the specific floating platform design and site conditions (Eatough, 2021). The mooring system can be broadly categorized into two types: catenary and taut systems. The first one, recognized by its substantial footprint on the seabed, employs a combination of chains, steel rope, with added clump weights, or synthetic rope for implementation (Díaz et al., 2022). It boasts the advantage of easy installation and reduced cost. Moreover, the load is oriented horizontally, enabling the use of conventional drag embedment anchors. Conversely, the second one, comprised of tendon lines linking the platform to the seabed, applies the principal load in the vertical direction. Consequently, the anchor system must endure this force to stabilize the floating platform. This mooring type is predominantly employed in floating wind turbines with TLPs; however, extensive studies are evaluating its applicability in deep waters where the economic feasibility of catenary solutions is limited (Eatough, 2021). Nevertheless, this mooring system's usage is constrained by the requirement for highly elastic mooring, intricate installation procedures, and its unsuitability for locations prone to seismic activity, despite its minimal seabed footprint (Eatough, 2021). Mooring options like catenary, taut, and semi-taut systems use materials such as steel, synthetic materials, or chains, while tendons typically consist of steel cylinders or solid rods. Selecting the most suitable mooring type depends on several factors, including the site's meteorological conditions, geotechnical characteristics, and water depths.

A range of anchor options, gravity anchors (deadweight anchors), anchor piles, drag embedment anchors, vertical loaded anchors, suction caissons, suction embedded plate anchors, torpedo anchors, and deep penetrating anchors (or dynamically embedded anchors) (Eatough, 2021; Wu et al., 2023), can be chosen depending on seabed composition and the mooring system type.

2.1.4 | Electrical transmission system

The electrical transmission system of a floating offshore wind farm is a critical element in efficiently harnessing and delivering renewable energy from dynamic marine environments. Multiple studies are analyzing which transmission technology would be more cost-effective and economically viable (Jiang et al., 2022; Lanni et al., 2023). Among all the components needed for the Electrical Transmission System, the most important are cables and substations. For floating offshore platforms, dynamic cables are required to withstand harsh environments and platform movements. This type of cable needs a range of auxiliary components including bend stiffeners, connectors, buoyancy modules, touchdown protections and transition joints (Eatough, 2021). Intra-array cable usually transmits current via high voltage alternating current (HVAC), ranging from 33 to 132 kV for intra-array cables. Concerning export cables, voltages range from 220 to 380 kV depending on the wind farm size. As the distance between wind farms and the shore increases to harness the best wind resource, high voltage direct current (HVDC) transmission becomes more cost-effective (DNV, 2022; Jiang et al., 2022; Lanni et al., 2023). Dynamic cables are not yet mature, however, they are expected to be commercial by 2028. To minimize the fatigue on the cable, different configuration options are being studied, with an overview of each reported in Eatough (2021). The fundamentals for HVDC submarine cables are the same as those of HVDC land cables, except for mechanical features. According to DNV (2022) they are qualified and commercially available up to ±525 kV. The offshore substation serves as a hub for collecting and conditioning power from multiple turbines before transmitting it to shore to minimize power losses during export (Eatough, 2021). It houses step-up transformers, switchgears, AC to DC converter (if needed), and other control equipment. The substation can be installed on a floating or bottom fixed platform. The floating platform designs are adapted from those of the floating offshore wind turbines, with higher weight (4500 Mt against 1200 Mt for a 12 MW wind turbine), and a lower center of gravity (DNV, 2022). In contrast, the bottom-fixed platforms are similar to those used in the oil and gas sector. To date, the only floating offshore substation in the world was installed in 2013 in Fukushima, handling a total of 16 MW and exporting power at 66 kV (DNV, 2022).

2.2 | Technology challenges

The "grand" challenges for the wind energy sector as a whole, are reported in an important document (Veers et al., 2022), produced within the framework of the International Energy Agency. Some of these challenges, such as those related to atmosphere knowledge, wind turbines, plants and grid, are relevant to onshore and offshore wind technology. However, floating wind in the Mediterranean Sea presents specific technological challenges. These challenges primarily arise from the early stage of maturity of floating offshore wind turbines and the regional offshore wind supply chain. These factors have a significant impact on associated costs and the feasibility of the projects (Castro-Santos et al., 2016; CATAPULT, 2016; Crown Estate Scotland, 2018; NREL, 2016). Cost reduction pathways necessitate actions in various area, including metocean and seabed measurements, foundation design, manufacturing, transport, installation improvements, and economies of scale (Wiser et al., 2016).

Access to reliable metocean data is crucial for planning the installation, operation, maintenance, and decommissioning of offshore wind projects. It guides decisions regarding weather windows and aids in accurate cost and production predictions for the wind farm. In situ measurements provide the most reliable information and should always be incorporated into the design of new wind farms. However, obtaining offshore wind and wave measurements can be very expensive, especially for deep-water sites. Consequently, the cost of metocean measurement campaigns represents a significant initial hurdle in project reliability assessment and risk analysis. The improvements of the knowledge of environmental parameters, such as the advancements in satellite-derived bathymetry (Viaña-Borja et al., 2023) could be beneficial for design optimization and cost reduction. To secure continuous, clean, and reliable measurements over extended periods in such challenging conditions, cutting-edge technologies are essential, some of which are still in the developmental stage (Ellul et al., 2016; Mathias et al., 2021).

Another technology challenge pertains to the turbine drivetrain, including the assessment of the optimal technology between direct-drive and gearbox configurations, as well as the growing demand for rare-earth raw materials required for its construction (IEA, 2023c).

Technological improvements and cost reductions are also needed in floating platforms, mooring and anchoring technologies. Nowadays, floating platforms for wind energy operate in seas with depth ranging from 50 to 120 m (Alhmoud & Wang, 2018; Bento & Fontes, 2019). Moving to deeper sea poses significant challenges, especially for mooring and anchoring systems (Singhal et al., 2019). Scaling up usually allows for a reduction in overall costs by increasing power per unit, but floating offshore wind technology introduces new issues related to load dynamics due to platform and wind turbine coupling, as well as platform stability and mooring system issues (Bianchini & Papi, 2022). Floater technology also impacts construction, transport, and decommissioning operations and costs. New concrete-based designs require substantial concrete production and robust heavy-load port infrastructure. On the flip side, steel-based concepts provide enhanced performance and fewer design issues, especially regarding platform–wave interaction and life assessment. Nevertheless, obtaining the required steel for new installations poses a critical challenge to the present steel production chain (Li et al., 2022).

Wind turbine technology is advancing toward larger scales, but the absence of reliable operational data introduces uncertainty in the design of turbine assembly and its life assessment. Consequently, validating computer-aided engineering tools for floating offshore wind turbine becomes crucial. This underlines the importance of scaled and pilot projects in the development of wind engineering software (Hmedi et al., 2023). For instance, prototypes like BlueH tension leg platform (TLP) in Italy (Collu & Borg, 2016), Statoil's Hywind spar in Norway (Skaare et al., 2015), WindFloat semi-submersible in Portugal (Roddier et al., 2010), and FLOATGEN barge in France (Galván et al., 2018) were developed through industry-academia collaboration. Research institutes, universities, and industry entities are collaboratively working to expedite the development of knowledge, methods, and tools aimed at addressing the new design challenges posed by floating offshore wind turbine technologies. This collaboration is evident in various dedicated tasks under the International Energy Agency Wind Energy Technology Collaboration Programme. Challenges concerning large-scale manufacturing, assembly, transportation, and accommodation of floating wind turbines components are analyzed in Section 4.4. Concerning the peculiarities of the Mediterranean Sea environment, in terms of wind turbines, the aerodynamic profile of the blades should be adequate to convert low wind speeds, which are more prevalent compared to the North Sea and Ocean. Further details on these conditions are provided in the next section. Currently, all offshore wind turbine manufacturers are based in Northern Europe or Asian countries, and commercial turbines do not feature optimized profiles for the Mediterranean area. Regarding platforms, the offshore environmental conditions in the Mediterranean are generally less severe compared to other offshore areas, suggesting the potential for lighter structures. However, conditions vary significantly from site to site. Site-specific optimization procedures and models are discussed by Ferri and Marino (2023) and Cottura et al. (2021).

Long-distance power transmission from offshore wind farms to onshore grids, along with the development of potential power storage systems, remains an ongoing area of development. Additionally, the design and production of dynamic cables for suspended wind farm connections are under active development (Ibrahim et al., 2022; Sant et al., 2018; Zhou et al., 2023).

Ports play a crucial role in the assembly, installation, and operation of floating offshore wind turbines. Port infrastructure needs to be ready for commercial-scale projects, where shipyards capable of managing operations on multiple FOWTs simultaneously. This involves supporting the weights during construction and ensuring easy access to the sea (Crowle & Thies, 2022). Operation and maintenance (O&M) present challenges, including the impact of the marine environment on structural life and system performance. High O&M costs result from difficulties in access, transport, and safety, especially for far shore wind farms. Therefore, cost reduction efforts involve minimizing human inspections through the use of remote operations, such as automated vehicle inspections and predictive maintenance (Hill, 2020). Decommissioning, repurposing, repowering and end-of-life challenges are associated with the need to handle large material volumes and address safety concerns similar to those encountered during the installation phase of marine operations (Li et al., 2022).

Lastly, a crosscutting challenge is represented by digitalization. Enhanced data availability, intelligent processing, and controls contribute to achieve "*improved efficiency and greater insight, ultimately leading to increased energy capture and significant savings for wind plant operators, thus reducing the Levelized Cost of Energy*" (Clifton et al., 2023).

2.3 | Environmental conditions

Various environmental conditions must be considered to accurately estimate the overall potential of Mediterranean Sea and reduce the energy production cost. These conditions encompass factors such as the available wind resource, bathymetry, extreme sea conditions, waves, and currents. Research on environmental and metocean conditions is crucial for selecting the most suitable technology. For instance, the seabed influences mooring lines and anchor systems (Lerch et al., 2018), while ocean current speeds or depth determine the use of a fixed or floating structure. Additionally, the wind-wave correlation has an impact on the choice of floater type. A comprehensive understanding of weather, metocean, and site conditions is essential not only for technical evaluation, but also for economic analysis due to its direct correlation with energy production. In the equation provided by Lerch et al. (2018), the available wind energy ($E_{\text{available}}$) is defined as:

$$E_{\text{available}} = \Sigma P_{\text{metocean}} \cdot H_{\text{metocean}} \cdot 8760,$$

where P_{metocean} is the power generated by a specific wind turbine under a given metocean condition and H_{metocean} is the occurrence probability per year of this metocean condition.

2.3.1 | Resource

The available wind resource stands out as one of the most crucial parameters in the preliminary analysis of techno-economic feasibility of wind farms. While real measurement data is preferable, especially for detailed design studies, there are instances where it is necessary to turn to different types of data sources, such as reanalysis wind data or satellite-based data (Zheng et al., 2016). Identifying the optimal sites for the development of offshore wind farms is influenced by factors such as mean values of wind speed, seasonal variability, and direction from which wake effects and turbine alignment depend (Castellania et al., 2015; Soukissian, Karathanasi, et al., 2017).

Compared to other European regions, such as the northern coast of the Iberian Peninsula (Castro-Santos et al., 2021) and countries facing the North Sea, the Mediterranean Sea presents lower wind energy potential. As indicated by various studies (Onea et al., 2016; Pantusa & Tomasicchio, 2019; Soukissian et al., 2016), the most favorable areas in the Mediterranean include the Gulf of Lions, the sub-area west of Sardinia, the southern part of Sicily, and the Agean Sea, where the average wind speed generally ranges between 8 m/s and 10 m/s. Soukissian et al. (2016) conducted an analysis based on satellite data in the Mediterranean basin, incorporating a statistical evaluation of annual and seasonal variability for both wind speed and direction. The findings revealed that during the summer, the wind resource is lower compared to other seasons, except in the Aegean Sea due to the presence of the etesian winds. Furthermore, the Gulf of Lions exhibits the highest wind intensity values, albeit with less stability compared to other basins.

The Gulf of Genoa, the north Levantine Basin, the East Tyrrhenian, North Aegean Sea, and North Adriatic Seas exhibit the highest values of mean annual wind speed variability. In terms of interannual variability (IAV), the regions with the overall largest values of IAV include the Balearic, Ligurian, and Tyrrhenian Seas, as well as the North Aegean and the South coasts of Turkey. Wind direction variability is generally low, except in the western part of the Mediterranean Sea, encompassing the middle of the Alboran Sea, the West Algerian basin, the Balearic and the North Ligurian Seas. For more detailed studies on wind variability, refer to Soukissian and Sotiriou (2022).

Concerning the onshore and offshore areas in Italy, the wind atlas of Italy, EOLIAN, developed by RSE (Sperati et al., 2024), serves as a valuable tool for evaluating the wind energy resource. The most favorable areas, as mentioned earlier, include the Southern part of Sicily, the sea surrounding Sardinia, the Ligurian Sea, and the sea facing the East coast of Apulian region. These areas are primarily located offshore, with depths exceeding 60 m (Lanni et al., 2023). Some regions may be suitable for the installation of offshore bottom-fixed turbines, such as Emilia-Romagna - albeit with a lower energy potential, and selected areas in Northern Apulian and Southern Sicily region.

2.3.2 | Bathymetry and seabed

In contrast to the North Sea, the Mediterranean basin is characterized by deeper water (European Commission, 2020b). According to the foundation classification defined earlier, less than 10% of the overall surface of Mediterranean Sea has water depths between 0 and 60 m (Pantusa & Tomasicchio, 2019), while approximately 30% is between 60 and 500 m. As depicted in Figure 2, shallow waters below 60 m are in the Northern part of the Adriatic Sea and in a significant portion of the sea around Tunisia and Libya, as well as in other coastal zones, subject to limitations due to the minimum distance from the shore. Medium to high-depth waters, ranging from 60 to 1000 m, are found in the Strait of Sicily, the Aegean Sea and the Adriatic Sea.

As previously mentioned, the design and installation of offshore fixed foundation, mooring, and cabling systems are closely tied to seabed properties (Amjadian et al., 2023). Despite the importance of conducting detailed analysis for specific installation sites, some general information about the seabed substrate in the Mediterranean basin can be extrapolated from EMODnet (https://emodnet.ec.europa.eu/en), which has compiled data from various works conducted by European countries. The provided data come in different scales, with the most detailed ones covering smaller areas. In Figure 3, all scales are grouped, revealing that mud, sand and mixed sand/mud substrate are prevalent. Mixed sediment and rocks are present in the Strait of Sicily, while along Turkish coast in the Aegean Sea, coarse-grained sediment is observed.

2.4 | Offshore wind energy potential and projects in the Mediterranean Sea

2.4.1 | Overall potential

To the best of the authors' knowledge, the only work providing an estimate of the theoretical maximum annual offshore wind production for the Mediterranean Sea is that of Pantusa and Tomasicchio (2019). According to the authors, the

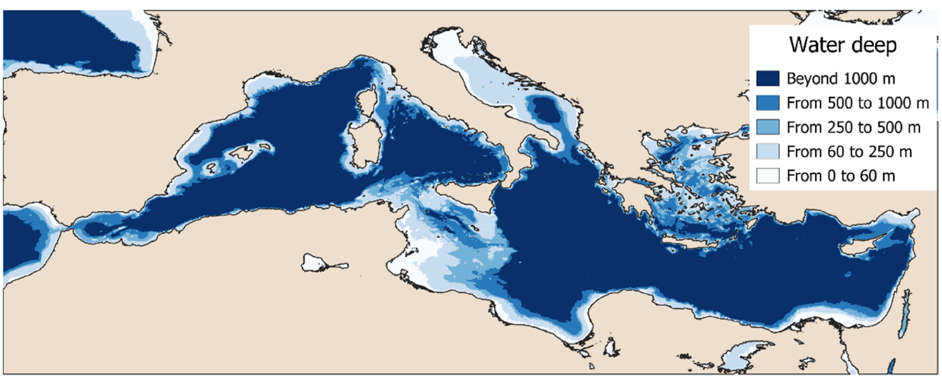

FIGURE 2 Bathymetry map generated by data from GEBCO (https://www.gebco.net/).

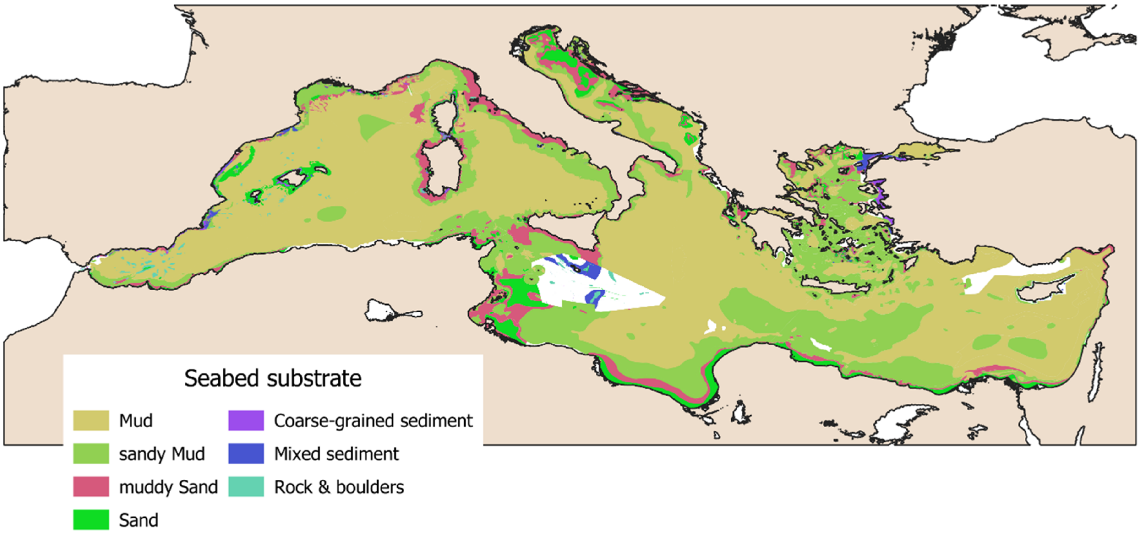

FIGURE 3 Seabed substrates from EMODnet data.

theoretical maximum annual offshore wind production for the basin is estimated to be around 742 TWh/year. It is important to note that this number, as emphasized by the authors, is a rough estimate only, as the particularities, especially the legal frameworks, of each Mediterranean area/country have not been taken into account. For instance, the authors excluded areas at a distance of less than 5 miles from the coast. However, the potential organized development areas in the Aegean Sea included in the draft National Programme for Offshore Wind Energy, are located within a distance of 6 nautical miles from the closest shore, see Section 2.4.3. The study specifically considered three depth categories (0–50 m, 50–250 m, 250–500 m), optimized wind farm layouts, and three types of turbines. The three different models of offshore wind turbines considered were rated at 3 MW (for water depths up to 50 m), 4.5 MW (for water depths between 50 and 250 m) and 6.15 MW (for water depths between 250 and 500 m). The lower and upper thresholds for the mean annual wind speed in the favorable areas were established at 4 and 8 m/s at 100 m above sea level. Importantly, marine protected areas were excluded from the analysis.

2.4.2 | Italy

According to the National Energy and Climate Plan (NECP, 2019), which received official approval from the European Commission in 2020, there were plans to install offshore wind farms totaling 0.9 GW by 2030. However, a new request for modification was submitted in June 2023, aligning with the new European climate package "Fit for 55." As a results of this modification, the revised expected offshore wind capacity target for 2030 is now set at 2.1 GW (PNIEC, 2023).

Regarding the requests for connection to the grid for offshore wind farms, the Italian Transmission System Operator TERNA reported receiving requests for approximately 40 GW in 2021 (IEA, 2023a), and 95 GW in 2022, with a significant concentration in the southern part of the country. Consequently, TERNA's "Fit for 55" scenario anticipates an installed capacity of 9 GW for offshore wind power. As of the end of September 2023, 80 offshore wind projects were submitted for environmental impact assessment (see Figure 4). As far as the authors are aware, none of these projects have obtained the required authorizations yet.

As of the present status, only one offshore wind farm, known as the Beleolico park, is grid connected in Italy. This wind park is situated in Taranto harbor and consists of 10 turbines, each with a power capacity of 3 MW, installed on fixed foundations (monopiles). Additionally, a small floating wind turbine with a capacity of 10 kW is undergoing testing in the Gulf of Naples to evaluate the technical feasibility of the system.

2.4.3 | Greece

As of the current legal framework, the exploration and identification rights for suitable areas for the development and installation of offshore wind farms within the Greek territory are exclusively held by the Greek state. In July 2022, a

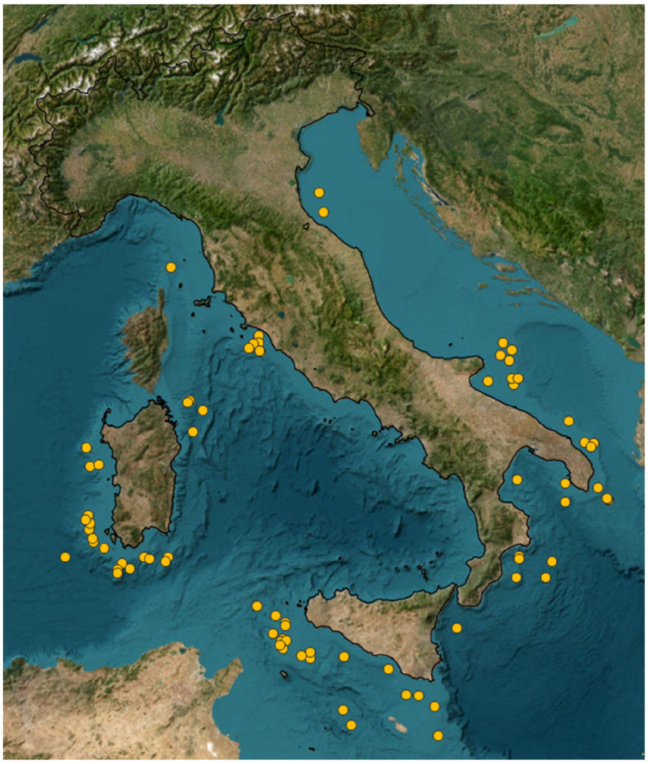

FIGURE 4 Position of offshore wind farms under environment impact assessment elaborated by RSE.

new legal framework, Law 4964/2022, A′ 150, was adopted regarding offshore wind development in the Greek Seas. The Hellenic Hydrocarbon and Energy Resources Management Company (HEREMA S.A.) is entrusted on behalf of the Greek State with the management rights related to research, exploration, and identification of offshore wind farms in organized development areas (ODA). The Independent Power Transmission Operator (IPTO) is designated as the responsible entity for developing links between the transmission grid and offshore wind farms, while the Regulatory Authority for Waste, Energy and Water (RAEWW) is tasked with organizing competitive tender processes for the granting of operational aid for each ODA.

An initial step toward the realization of this initiative was the announcement of the draft National Development Program for offshore wind farm by HEREMA on October 31,2023 (HEREMA, 2023a). The program outlines 25 eligible areas for offshore wind farm development on a medium and long-term perspective, covering a total area of 2712 km^2 and estimating a minimum capacity of 12.4 GW. Most of the proposed offshore areas are deemed suitable for floating technology. Subsequently, the Strategic Environmental Impact Assessment (SEIA) for the ODA outlined in the program was released (HEREMA, 2023b). The SEIA was open for public consultation until the end of November 2023.

Figure 5 illustrates the potential organized development areas for medium-term development according to the draft National Development Program for offshore wind farm. These potential areas depicted in Figure 4, cover an area of 978 km^2 with a total estimated capacity of 4.9 GW. The draft National Development Program for offshore wind farm is expected to be approved through a Joint Ministerial Decision.

2.4.4 | France

Offshore wind power is a key component of France's strategy to diversify its energy mix and achieve its ecological transition goals, aiming to produce 40% of electricity from renewable sources by 2030. The national offshore wind development program has an ambitious target of constructing around 50 offshore wind farms by 2050, with a total capacity of 40 GW, contributing to nearly 20% of France's electricity consumption. The Programmation pluriannuelle de l'énergie (Multiannual Energy Plan), published in April 2020, outlines several calls for tender to award offshore wind projects along France's various maritime fronts: Channel, North Sea, Atlantic and Mediterranean. Specifically, for the

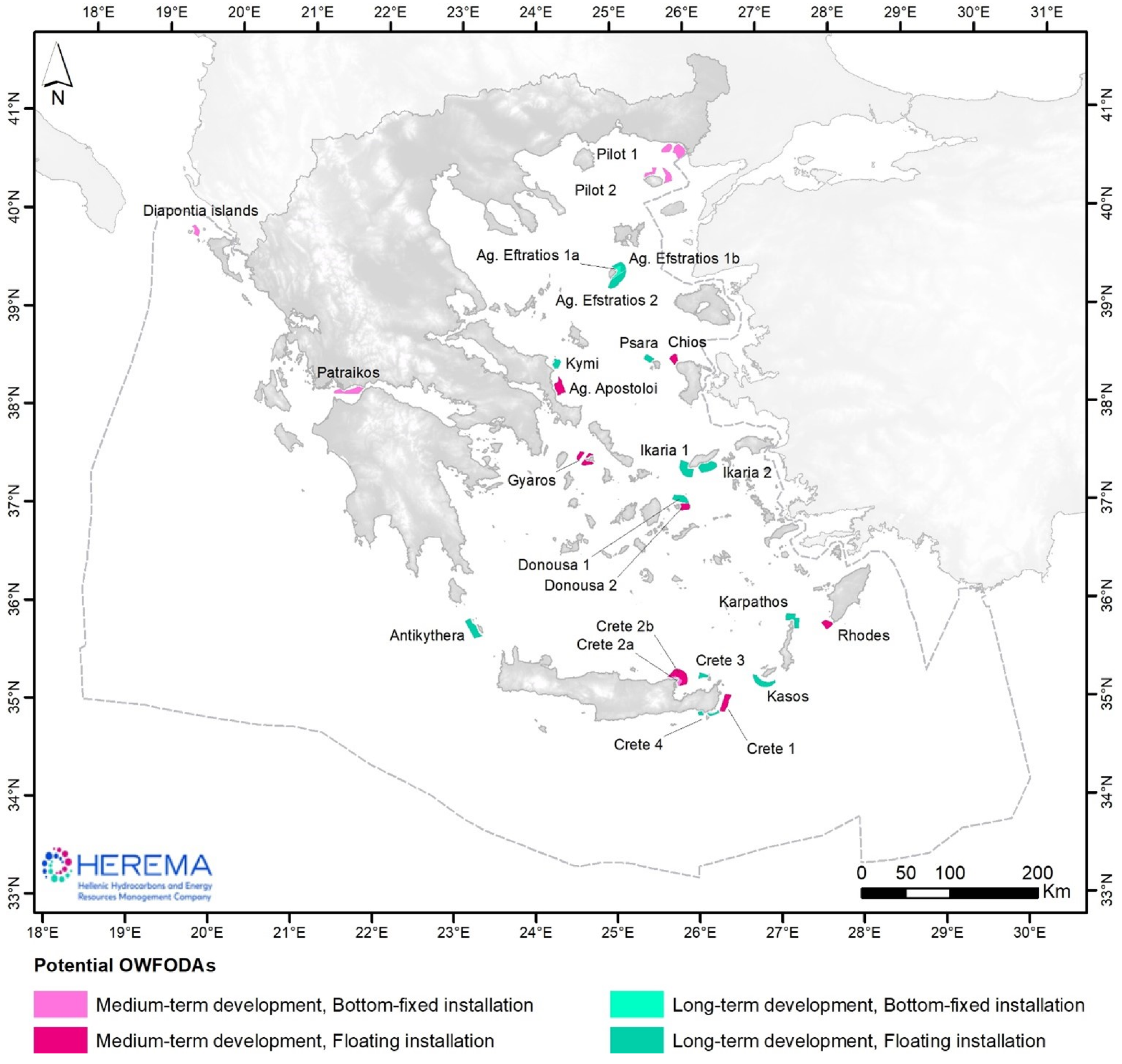

FIGURE 5 Potential organized development areas according to the draft National Programme for Offshore Wind Energy. *Source*: Modified and provided by HEREMA S.A.

Mediterranean Sea, the Multiannual Energy Plan calls for two floating offshore wind farms of 250 MW each to be awarded in 2022, with the possibility of expanding to 750 MW each in a second phase. Competitive tendering procedures have been initiated following the public debate to select winning bidders responsible for building and operating the future offshore wind farms. The techno-economic conditions assessed for the Mediterranean region indicate favorable factors, including high wind resource, moderate wave climatology, and low tidal range and tidal currents, making it conducive for the development of floating wind turbines. The target feed-in tariff of the electricity produced, as set in the annual energy program, is 110 €/MWh. In parallel, a program initiated in 2015 by ADEME (French Environment and Energy Management Agency) to develop pilot sites for floating offshore wind power is underway. This program is expected to Lead to the commissioning of three pilot sites, whose main characteristics are summarized in Table 1 and in Figure 6.

TABLE 1 Characteristics of the three floating wind pilot projects in France Mediterranean area (www.ecologie.gouv.fr/parcs-eoliens-en-mer-mediterranee-gouvernement-annonce-selection-13-candidats-participer-deuxieme).

Pilot site	Total installed power [MW]	Number of wind turbines	Turbine power [MW]	Type of float	Distance to shore [km]	Site area [km^2]	Expected commissioning date
Leucate Le Barcarès	30	3	10	Semisubmersible	16	6.17	2024
Gruissan	30	3	10	Barge	18	8.15	2024
Faraman Port Saint-Louis du Rhône	24	3	10	Tension leg platform	14	0.78	2024

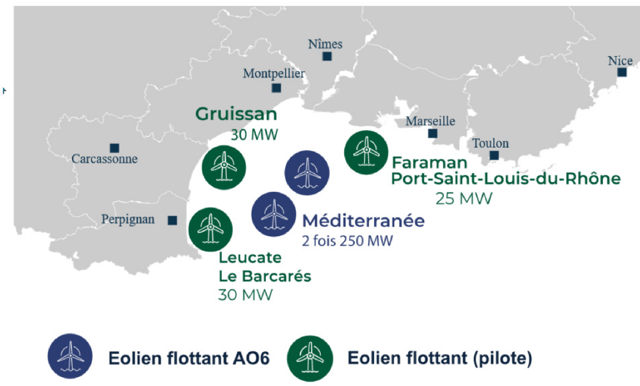

FIGURE 6 France Mediterranean sites for offshore floating wind (www.eoliennesenmer.fr/facades-maritimes-en-france/facade-mediterranee).

TABLE 2 Characteristics of the offshore wind projects in Spain East Mediterranean area.

Name of the project	Installed power [MW]	Area	Enterprise
Tramuntana	500	Girona (Cataluña)	Bluefloat Energy and Sener
Gavina	500	Girona (Cataluña)	Iberdrola
Medfloat Pilot Parc	50	Girona (Cataluña)	Saitec
Catwind	1000	Girona (Cataluña)	Grupo Cobra
L'Empordá	510	Girona (Cataluña)	Capital Energy
Creus	510	Girona (Cataluña)	Ferrovial

2.4.5 | Spain

The Ministry for Ecological Transition and the Demographic Challenge of the Spanish Government unveiled the "Roadmap for the development of offshore wind and marine energy in Spain" in 2022, outlining goals for offshore wind development in the country: ranging from 1 to 3 GW by 2030.

As of now, 18 enterprises have submitted projects to this Ministry for various coastal areas in Spain. Specifically, for the Spanish shore of the Mediterranean Sea (MITECO, 2022), the characteristics of the proposals are reported in Tables 2 and 3. Some proposals in the South of Spain may face challenges in development as they are not situated in the POEM area (POEM—Planes de Ordenación del Espacio Marítimo or MSP—Maritime Spatial Planning).

TABLE 3 Characteristics of the offshore wind projects in Spain South Mediterranean area.

Name of the project	Installed power [MW]	Area	Enterprise
Mar de Ágata	300	Almería (Andalucía)	Bluefloat Energy and Sener
Alwind	300	Almería (Andalucía)	Grupo Cobra
Nao Victoria	1000	Málaga (Andalucía)	Iberblue Wind España
Albaicín	500	Granada (Andalucía)	Capital Energy

3 | COSTS ASSESSMENT AND ECONOMIC CHALLENGES

3.1 | Criteria and models

According to Pires et al. (2022) the most commonly used parameters for assessing the economic viability of an offshore wind farm are: the levelized cost of energy (LCOE) or electricity, which is applied to electricity production plants like onshore and offshore wind farms (Castro-Santos et al., 2021; IEA-NEA, 2020), the net present value (NPV), the internal rate of return (IRR), the discounted payback-period (DPBP) and life cycle cost analysis (LCC) (Maienza et al., 2022). LCOE is the most used parameter and, more generally, serves as the principal tool for comparing plant-level costs averaged over the lifetime. Consequently, it is used to compare different technologies or different settings within the same technology at the same location. Equation (1) sets out the LCOE in Aldersey-Williams and Rubert (2019) definition.

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{C_t + O_t + V_t}{(1+d)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+d)^t}}, \tag{1}$$

where C_t is the capital cost, O_t the fixed operating cost, V_t the variable operating cost in period t, E_t the energy generated in period t, d the discount rate, and n is the economic lifetime of the plant. LCOE is generally expressed in €/MWh. Equation (2) sets out the simple Levelized cost of energy (sLCOE) defined by NREL for plants with no fuel costs like the wind farms (Beiter et al., 2021).

$$\mathrm{sLCOE} = \frac{(C_0 \cdot \mathrm{CRF} + \mathrm{O\&M})}{8760 \cdot \mathrm{CF}} + V, \tag{2}$$

where C_0 represents the overnight capital cost, O&M denotes the fixed operating cost, V stands for the variable operation cost, CF represents the capacity factor of the plant (which is the ratio of the average yearly net energy production to the plant's nominal capacity), and CRF is the capital recovery factor. CRF depends on weighted average cost of capital (WACC) and the economic lifetime of the plant.

According to Beiter et al. (2021) the "*sLCOE does not account for financial costs of a specific projects in a specific market, however it is widely used in the renewable sector especially for long term analysis.*"

The second, and equally important, parameter is NPV, defined as "*the net value of the cash flows of the plant considering its discount from the beginning of the investment*," as presented in Equation (3) (Castro-Santos et al., 2021).

$$\mathrm{NPV} = -I_0 + \sum_{t=1}^{n} \frac{\mathrm{CF}_t}{(1+d)^t}, \tag{3}$$

where I_0 is the initial investment of the project and CF_t is the operational cash flow at year t.

Evaluating economic parameters in a sector at its very beginning, such as offshore wind energy sector in the Mediterranean basin, entails a very high degree of uncertainty. Most of the evaluations refer to fictional and/or generalized cases, and the lack of experience in the sector introduces additional uncertainty (DEA-DNV, 2023; Martinez & Iglesias, 2021). A tentative model based on the first data from Hywind Scotland Pilot Park is proposed in Sykes et al. (2022) and a minimalistic approach is proposed in Sørensen and Larsen (2021). However, there are still significant sources of uncertainty that affect LCOE calculations, including uncertainty in offshore wind resource estimation due to the lack of direct long-term measurements offshore and possible variations in the wind resource characteristics in the medium to long-term due to the climate changes (Castro-Santos et al., 2021; Serri et al., 2020). The uncertainty in technology performance affects the evaluation of the energy production and its reliability that affects the O&M costs. Capital costs carry significant weight in LCOE calculations and depend on various factors, including: site characteristics (distance from farm to the shore, distance from farm to the shipyard, water depth, seabed conditions), type of technology (fixed structures such as monopiles or jackets or floating platforms such as semisubmersible, TLP or spar), the number and size of turbines, and the electrical export transmission system technology and characteristics (HVAC, HVDC) (Lanni et al., 2023). Moreover, capital costs are influenced by the readiness of the supply chain (Umoh & Lemon, 2020) and the level of maturity of certain components, including dynamic cables for the floating wind turbines and HVDC cables and equipment for long-distance electricity transport to shore (Lanni et al., 2023). Uncertainty regarding financial parameters, such as WACC, is contingent on investors' confidence and can vary from one country to another, depending on the strength and long-term credibility of sector policies and supports (Serri et al., 2020). When performing a comparison analysis of LCOE across various regions and scenarios, it is crucial to consider that in some cases, the expenses associated with the export system might not be factored into the capital costs. For instance, in some cases in Belgium, Denmark, France and Spain the export system is either constructed by the Transmission System Operator or funded by governmental bodies. Lastly, according to Aegir (2023), "*Levelized Cost of Energy values for offshore wind projects can be represented in Real (adjusted for expected inflation) or Nominal (without any adjustment), pre-tax or after-tax terms. Understanding the difference between these common LCoE calculations is essential for accurate project comparisons*."

NPV calculation needs to include an estimation of plant revenues, primarily from electricity sales. However, it is important to note that this parameter has a high level of uncertainty too. In many countries, there are already incentive measures in place, or they are expected to be applied in the future. Nonetheless, in the Mediterranean countries at present, it is generally not known the kind of intervention, its duration and the base tariffs. For example, the unique operating offshore wind farm in Italy benefits from a feed-in-tariff incentive of 165 €/MWh for a duration of 25 years. However, in the case of Spain the electric tariff for renewable energies during last 15 years has suffered a lot of uncertainty, changing depending on the Government (B.O.E., 2013). Other ways to sell electricity include private to private contracts (such as Power Purchase Agreements) and direct market selling, whose tariffs are hard to be assessed for the next decades. Some of the above-mentioned parameters can be taken from studies and experiences with fixed offshore wind farms that have been operating for more than 10 years in the North Sea. However, it is not simple to adapt these parameters for the Mediterranean contest where floating gigawatt-scale farms are expected to be installed (Martinez & Iglesias, 2021).

Despite all various sources of uncertainty, assessing the economic viability of a particular technology, especially an emerging one like floating wind, is highly valuable for all stakeholders, especially policymakers (IRENA, 2016; Martinez & Iglesias, 2021; Serri et al., 2020).

The consideration of the temporal horizon in economic evaluations is crucial, especially when dealing with developing technologies. The concept of the learning curve is fundamental to understanding how costs evolve over time. As described by Rubin et al. (2015), the learning curve represents "*the fractional reduction in cost for each doubling of cumulative production or capacity*." In the context of floating offshore wind, a decrease in costs is expected as the industry matures, and more capacity is installed. This is in line with the learning curve effect, where experience, technological advancements, and economies of scale contribute to cost reductions. However, predicting the specific rate at which the offshore wind sector will grow, and costs will decrease can be challenging. In the absence of clear visibility into the growth rate, analysts often refer to the learning curves of similar, more established technologies to make informed assumptions. For example, the learning curve for offshore floating technology may be assumed to be similar to that of offshore fixed-bottom technology, providing a basis for economic evaluations over the medium to long-term.

Another way to assess the effects of large-scale deployment on the economy is to evaluate the reduction of LCOE in relation to a known value at a fixed year. For example, according to Wiser et al. (2021) between 2020 and 2050, the LCOE for offshore fixed-bottom wind energy sector is expected to decrease from around 70 to 40 US$/MWh in a median scenario for Europe, and between 2025 and 2050 the LCOE for offshore floating wind energy sector is expected to decrease from around 90 to 45 US$/MWh in the same scenario. According to DNV (2022) "*the first floating wind farms have seen LCOE exceed 200 US$/MWh*," but a drop in LCOE to less than 100 US$/MWh and 40 US$/MWh is expected in 2025 and 2050, respectively. Wiser et al. (2021) also presents similar LCOE values, slightly higher in 2025 and around 50 US$/MWh in 2050 (see Figure 7).

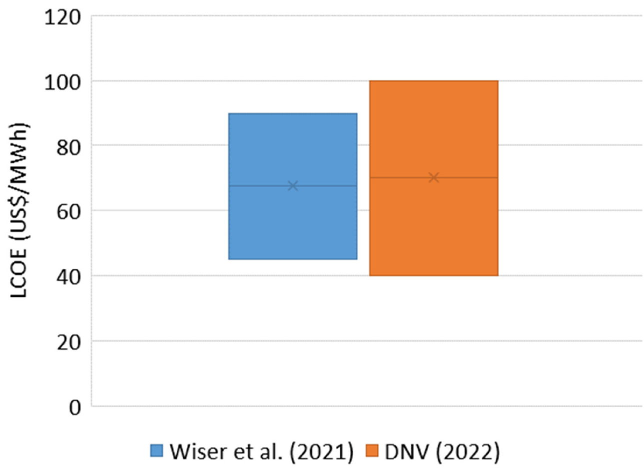

FIGURE 7 Variations in LCOE (US$/MWh) of floating offshore wind from 2025 to 2050 for different authors. *Source*: Own elaboration.

It is important to highlight that these LCOE values are referenced to geographical areas with an average wind resource higher than that of the Mediterranean. The subsequent section will focus on the cost of offshore wind energy specifically in the Mediterranean area, taking into account the unique conditions of this region.

3.2 | Case studies in Italy and in the Mediterranean Basin

A comprehensive literature review on the economical parameters of offshore wind energy in the Mediterranean basin and the countries adjacent to it has been conducted. Assessments concerning fixed technology has been included too to give a more comprehensive view. The key findings from these studies are summarized in Table 4 and Figure 8. It is important to acknowledge that different parameters and assumptions have been employed to determine these studies' LCOE and NPV. Therefore, the comparison offered serves as a rough guide, bearing high uncertainty.

To the best of the authors' knowledge, no economic viability studies for offshore wind farms are available for the countries facing the Mediterranean basin not included in Table 4. France and Spain primarily focus on their windier Northern offshore areas (Castro-Santos et al., 2021; El Kinani et al., 2023). Other countries have initiated investigations into offshore wind resource characteristics and wind power potential: Croatia (Liščić et al., 2014), Montenegro (Burlando et al., 2009), Albania (Ago, 2019), Cypus (Akylas et al., 2020; Hadjipetrou et al., 2022), Lebanon (Ibarra-Berastegi et al., 2019), Syria (Eivo et al., 2020), Tunisia (Attig-Bahar et al., 2021), Algeria (Boudia & Andrade Santos, 2019), and Morocco (Taoufik & Fekri, 2021). The remaining countries are likely more focused on onshore wind energy deployment.

Some considerations about the data reported in Table 4.

- The average LCOE value is around 90–100 €/MWh, in line with almost all the studies apart higher values in Aquilina et al. (2014) and in Pantusa et al. (2020) and lower values in Abdelhady et al. (2017).
- As expected from the resource map, the lowest LCOEs correspond to geographical areas with high resource such as Gulf of Lion and the Aegean Sea.
- As expected LCOEs for fixed foundation wind farm are lower than the floating ones.
- As expected, LCOEs are lower in recent studies or studies concerning future scenarios due to a general increase in the size the wind farms, best performance of wind turbines and cost reduction due to learning curve principle.
- Most of the studies concern well-developed countries belonging to European Union with comparable costs for material and manufacturing.

The variations in LCOE for a restricted group of studies have been reported in Figure 8. Most of the results align with those calculated for the overall region (Martinez & Iglesias, 2021). Specifically, three results are close to the lower part of the Mediterranean one: Serri et al. (2020) and Travaglini et al. (2023), both reporting costs during the

TABLE 4 Summary of technical and economic parameters of offshore wind farms according to the cited studies.

Reference	Geographical area	Technology	Wind farm size	LCOE	NPV	Temporal scenario
Martinez and Iglesias (2021)	Mediterranean	Floating	1000 MW	~95 €/MWh (Gulf of Lion, Aegean Sea) 130–180 €/MWh (South Spain—Alboran Sea, Sardinia, Sicily Malta, South Adriatic Sea) >250 €/MWh (Balearic Islands, North Adriatic, Tyrrhenian, Levantine Seas)	–	–
Ghigo et al. (2020)	Italy (Pantelleria Island)	Floating	10 MW	100–125 €/MWh (Hexafloat platform)		2030
Maienza et al. (2020)	Italy (Southern site)	Floating	125 MW	Av. 9.74 c€/kWh (semisubmersible, tension leg, spar buoy)	–	–
Pantusa et al. (2020)	Italy (Brindisi—Apulian region)	Floating	–	269–334 €/MWh (TLP) 303–404 €/MWh (spar buoy) (WACC 4 and 8%)	–	2030
Schweizer et al. (2016)	Italy (Northern Adriatic Sea)	Fixed	54 MW 216 MW	–	17.11 M€ (best value)	–
Serri et al. (2020)	Italy	Floating	1000 MW	63–156 €/MWh 40–110 €/MWh (different CF and WACC 5%, 7% 9%; possible average wind energy reduction at 2060)	–	2030 2060
Travaglini et al. (2023)	Italy (Sardinia Island)	Floating	1005 MW	95–121 €/MWh (10 MW turbine) 92–118 €/MWh (15 MW turbine) WACC 5%, 7%, 9%	–	2030
Zountiouridou et al. (2015)	Greece (Santorini island)	Floating	12.33 MW	–	0–30 M€ different economic schemes	–
Konstantinidis et al. (2014)	Greece (Limnos island)	Fixed (Jacket)	125 MW	87.92 €/MWh	96.7 M€	2012
Cali et al. (2018)	Turkey (Bozcaada island Bandirma, Gokceada island)	Fixed (monopile)	802.8 MW (Bozcaada) 349.2 MW (Bandirma) 266.4 MW (Gokceada)	81.85–109.55 US$/MWh 100.73–135.97 US$/MWh 85.28–112.09 US$/MWh	943.4 M€ 613.8 M€ 336.1 M€	–
Satir et al. (2018)	Bozcaada island	Fixed	90 MW	91.03 €/MWh	48.3 M€	–
Aquilina et al. (2014)	Malta	Floating	100 MW	21.0–23.6 c€/kWh (different turbine size)	–	–
Abdelhady et al. (2017)	Egypt	Fixed (monopile)	Based on single 7 MW turbine	0.075–0.079 US$/kWh	–	–

commercial phase, and Ghigo et al. (2020) who study a very windy site near Pantelleria Island. Aquilina et al. (2014) also investigate a windy site close to Malta, but the paper is older, 2014, and at that time the floating wind technology was in an earlier development stage and costs were estimated higher than in more recent studies. The higher LCOE values found by Pantusa et al. (2020) are mainly due to quite low capacity factors, around 15%.

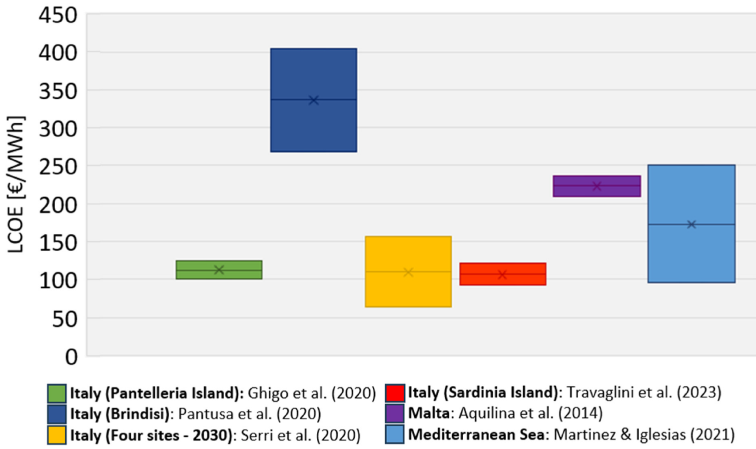

FIGURE 8 Variations in LCOE (€/MWh) of floating offshore wind for different authors and locations along Mediterranean Sea. *Source*: Own elaboration.

3.3 | Economic challenges

The main economic challenge for the offshore wind sector, is the cost reduction (Kausche et al., 2018). On one hand, capital, operational, and maintenance costs could be decreased through economies of scale. Technology and digital improvements have the potential to increase wind farm production, that is, through novel turbine and farm control strategies (Masoumi, 2023) or reaching a consensus on platform design (Barter et al., 2020). On the other hand, the wind energy sector might face potential increases in material costs and manufacturing and shipping times, that led to a slowdown in offshore wind additions in 2023 (IEA, 2024).

Regarding profitability, the main challenge is linked to the presence and type of renewable policy and support systems, such as feed-in-tariffs (Kitzing et al., 2012). In the absence of support measures (Jansen et al., 2020), long-term power purchase agreements with utilities or corporate buyers can help ensure stable revenues and encourage investments in the sector (Busch et al., 2023). In addition, in the future electricity market some of the ancillary services that wind farms can provide for the grid, that is, participating in regulation and reserve markets, may be compensated (Edmunds et al., 2019). Despite the ongoing high costs of the offshore wind energy sector and some dissenting opinions (Lesser, 2020), European countries are actively promoting sector growth to maintain their leadership in the offshore wind market. According to ETIP Wind (2023), wind energy is projected to add 104.2 €billion to the EU GDP by 2030 under the REPowerEU plan. Regarding the floating wind sector, due to the newer technology and the associated market uncertainty, another big challenge is the reduction of the risk perceived by investors. Díaz and Guedes Soares (2023) assess that the high capital cost of floating wind technology is one of the main barriers for investors and propose a model that "*identifies the optimal solution for a floating farm depending on the economic and financial aspects associated*." One way to decrease this risk is the co-financing of the first floating wind farm projects, that is "*The European Investment Bank (EIB) announces the conclusion of three financing agreements, with the support of the European Commission, for installing and commissioning three floating offshore wind farms off the French Mediterranean coast*" (https://ec.europa.eu/commission/presscorner/detail/da/IP_22_4155).

4 | CONSIDERATION ABOUT FUTURE DEVELOPMENTS

Beyond purely technological issues and economic aspects, other factors will affect the offshore wind development in the Mediterranean Area. Non-technical such as environmental sustainability, MSP, the regulatory framework, system integration and the supply chain are briefly addressed in this section.

4.1 | Environmental sustainability

As already mentioned, offshore wind energy, along with the rest of renewable energies, is identified as one of the most crucial measures for climate mitigation and adaptation (Soukissian et al., 2023). From an economic perspective, the global climate value of offshore wind energy, considering reductions in emissions and abatement costs, is estimated to be—in billion US$—100 (without climate policy), 120 (with a limit on permissible carbon emissions), and 450 (with significant carbon taxes) (Cranmer & Baker, 2020). The Offshore Renewable Energy Strategy (European Commission, 2020a) outlines the necessity to increase the installed offshore wind capacity in European waters to at least 60 GW in 2030 and at least 300 GW in 2050. In this context, the Mediterranean Sea is expected to play a pivotal role.

On the other hand, it is important to consider offshore wind farm environmental impacts to make the huge planned offshore wind as sustainable as possible. In Galparsoro et al. (2022) it is pointed out how environmental effects in general, and ecosystem effects in particular, are still poorly investigated in offshore wind energy planning. It is essential to consider cumulative impacts and assess them through effective MSP processes in order to select the best spots for new wind farms preserving healthy oceans and seas as called for in the United Nations Sustainable Development Goal (SDG) 14 (https://sdgs.un.org/2030agenda) and also satisfying the EU Biodiversity Strategy goals (Díaz et al., 2022).

Another aspect to be considered is climate change which may also impact offshore wind energy itself. For an in-depth review on this subject, refer to Solaun and Cerdá (2019). The most recent analysis of the potential climate change impacts on Mediterranean offshore wind energy is provided by Martinez and Iglesias (2023). In their study, the authors assessed the impacts of the latest climate change scenarios (SSP1-1.9/low emissions, SSP2-4.5/business-as-usual, and SSP5-8.5/intensive fossil-fuel consumption) on wind power density.

Under scenarios SSP2-4.5 and SSP5-8.5, significant progressive reductions in wind power density and increased variability are anticipated toward the long-term future (approximately 20% for SSP5-8.5), with more pronounced effects in the Western Mediterranean. Conversely, under the low emissions scenario, increased wind power density is exhibited for the Italian Seas, particularly the Gulf of Genoa, certain parts of the Adriatic Sea, and the southern Tyrrhenian Sea, across all examined future time periods (near-term 2030–2039, mid-term 2060–2069, and long-term 2090–2099). Serri et al. (2020) investigated the long-term impact of climate changes on the economic sustainability of offshore wind farms in Italy.

4.2 | Maritime Spatial Planning and regulatory framework

To achieve the ambitious offshore wind targets set by the Offshore Renewable Energy Strategy (European Commission, 2020a), many marine areas will be deployed for energy production and connection to the power transmission grid. The Maritime Spatial Planning is the right and necessary tool for public authorities to identify sites for new wind farms by assessing their environmental, social and economic impacts. By doing so, it would be possible to allow coexistence with other uses of the sea, for example fisheries, shipping, and tourism, and improve the social acceptance of these installations (https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX%3A52020DC0741—offshore EU strategy).

In addition, a clearer and well-regulated market design is important to ensure long-term certainty to all bodies involved in the wind energy development. EU is making a big effort to have an electricity market design suitable for the expected huge amount of renewables and the proposed Energy Market Design (EMD) reform goes in this direction (https://www.consilium.europa.eu/en/press/press-releases/2023/10/17/reform-of-electricity-market-design-council-reaches-agreement/).

4.3 | System integration

To facilitate system integration, the possibility of hybridization with other types of offshore energy sources, primarily solar and wave has to considered in medium-long term. Especially in floating platforms different technologies could share mooring lines and anchor system, thereby reducing installation and operation costs (Soukissian, Denaxa, et al., 2017). Another advantage lies in the non-correlation between different sources to ensure greater system stability in terms of power production and to decrease seasonal fluctuations.

Combining wind farms with offshore solar power farms is useful to mitigate seasonal variability, as during summer, there is generally abundant solar radiation and less wind energy, while during winter, the opposite holds true. The most suitable zones for such complementarity are the Eastern Levantine Sea, the Northern coasts of Greece and Sicily, the Southern coasts of Italy, and the Northern coasts of Mediterranean in Spain (Soukissian et al., 2021).

Regarding wave-wind sources, although Gulf of Lions and Aegean Sea have greatest energy potential (both for wind and wave), they exhibit a high correlation factor thus do not appear to be favorable for hybridization systems. On the other hand, the most suitable areas with low values of the correlation factor are the body of water bounded by Algeria to the South, Sardinia to the North-East and Balearic Islands to the North-West, despite having a moderate energy potential (Ferrari et al., 2020). The exploitation of combined systems with wave energy are evaluated in Azzellino (2019), Kardakaris et al. (2021), and Contestabile et al. (2022). Specifically, in Azzellino (2019), an analysis of wind-wave correlation was performed, revealing that Tyrrhenian coast south of Elba Island, the Northern-western Sardinian coast off the town of Alghero, the Southern Tyrrhenian Sea off the Eolian islands, and the southern Adriatic and Ionian coastal waters are all good candidates with a high energy potential. In Contestabile et al. (2022), a case study of hybrid system located in the Gulf of Naples was presented. The reference project is MaRELab, and during autumn of 2021, a floating turbine demonstrator (1:10 scaled) was positioned to verify the technical feasibility of marine energy systems under operational conditions. The study focuses on the relevance of sea-breezes due to their occurrence during energy peak demand. Finally, in Kardakaris et al. (2021), the combined offshore wind and wave potential of the Greek Seas has been assessed with respect to the complementarity and synergy aspects between the two resources.

Another possibility to facilitate the integration of a large amount of offshore wind energy is the so-called Power-to-X (Fernández-Guillamón et al., 2019). Offshore wind energy can be utilized to produce other energy vector, such as hydrogen, methanol, or ammonia, distributed along their respective chains to the final user. Regarding hydrogen, various combinations are possible (ORE Catapult, 2020). If the electrolyzer is onshore, it is possible to mitigate offshore wind overproduction. If the electrolyzer is offshore, it is cheaper to transport hydrogen to the shore than electricity or both (Ibrahim et al., 2022). Lastly, in a long-term scenario, the use of superconducting DC cables cooled by liquid hydrogen to connect the offshore wind farm to the shore could be a solution to transport both energy vectors. Some studies and projects are already ongoing on this topic (www.rina.org/en/media/CaseStudies/scarlet-project).

4.4 | Supply chain

The offshore wind supply chain poses significant challenges. Raw and secondary materials demand for turbines, foundations and electric equipment, and their sustainability and recyclability (Li et al., 2022). Manufacturing facilities must be equipped to produce components of considerable size, such as blades, towers, foundations, and platforms (Wooley & Matos, 2023). Transporting these large components from various facilities, sometimes also located outside the installing country, to the assembly site near the shore is a complex task. The storage and assembly site necessitate a substantial amount of space near the shore, preferably close to a port, which can be problematic for countries with a high focus on tourism along their coastlines, such as those facing the Mediterranean basin. The adaptation of shipyards, traditionally accustomed to "project-based" construction, to function more like a typical manufacturing industry with a focus on "series production" is essential. For example, the Spanish vessel manufacturer Navantia Fene (A Coruña, Spain), which constructed the main floating offshore wind platforms for the world's first floating offshore wind farms, is reconfiguring its traditional slipways to accommodate more space for mass production (Navantia, 2023). Dedicated and specialized vessels are required for the installation of monopiles, jackets and cables, and currently, they are not present in the Mediterranean area. Maintenance vessels and trained crews are also essential (Chitteth Ramachandran et al., 2022). Another critical challenge is the concentration of the manufacturing of most offshore wind components, such as blades, nacelle, and towers, in only one Eastern country (IEA, 2023b). Moreover, more than 50% of the global manufacturing capacity and material production for wind systems are concentrated in five major enterprises (IEA, 2023b). These two factors could introduce a not negligible degree of uncertainty regarding supply times and costs, potentially causing delays in the development of the sector. However, for the floating wind systems, North Europe still appears to play a central role (Umoh & Lemon, 2020), and this role could be reinforced by the expected growth of industries in Southern European countries. The development of the supply chain for offshore wind, especially floating, in the Mediterranean countries represents a significant opportunity for national economic expansion and the creation of local jobs (Balanda et al., 2022). Moreover, countries like Italy have already a well-developed offshore wind industry, with long-term experience that could easier embrace this new offshore sector.

5 | CONCLUSIONS

To achieve the very ambitious decarbonization objectives by 2050, according to offshore wind projects in the pipeline, a significant deployment of offshore wind in the Mediterranean area is expected in the next decades, mostly using floating wind technology. The Mediterranean basin presents very different conditions in various areas, including wind resource amount, presence of infrastructures for offshore installation and grid connection, policies and regulations. In this area, the offshore wind energy sector faces many challenges today, including better knowledge of resource and environmental conditions, the maturity of floating technology, such as achieving consensus and standardization for platform design and dynamic cables, as well as cost reduction and presence of dedicated support systems and/or long-term purchase contracts. Costs assessment is subject to high uncertainty; however, international experts estimate average encouraging LCOE values around 90–100 €/MWh for the commercial stage. It is foreseen that Europe will act to maintain its leadership position in offshore wind energy market also fostering the Mediterranean offshore wind energy exploitation. The main challenges identified in this paper are to create a clear and favorable regulatory framework, to foster the development of the supply chain, to decrease costs—also with the use of digital technologies, and to reduce perceived risks with specific support measures, that is, incentives and long-term contracts. It is desirable that National Governments, Supranational Institutions and wind energy stakeholders will work together to overcome these challenges and accelerate the development of floating wind sector in the Mediterranean Area.

AUTHOR CONTRIBUTIONS

Laura Serri: Conceptualization (lead); methodology (lead); project administration (lead); writing – original draft (lead); writing – review and editing (lead). **Davide Airoldi:** Investigation (equal); methodology (equal); writing – original draft (equal). **Francesco Lanni:** Conceptualization (equal); investigation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal). **Roberto Naldi:** Investigation (equal); methodology (equal); writing – original draft (equal). **Alessio Castorrini:** Investigation (equal); methodology (equal); writing – original draft (equal). **Franco Rispoli:** Investigation (equal); methodology (equal); writing – original draft (equal). **Laura Castro Santos:** Investigation (equal); methodology (equal); writing – review and editing (equal). **Marc Le Boulluec:** Investigation (equal); methodology (equal); writing – original draft (equal). **Christophe Maisondieu:** Investigation (equal); methodology (equal); writing – original draft (equal). **Takvor Soukissian:** Conceptualization (equal); investigation (equal); methodology (equal); supervision (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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