Project co-financed by the European Regional Development Fund

Promoting innovative nEtworks and cLusters for mArine renewable energy synerGies in mediterranean cOasts and iSlands

# Diagnostic study of the Mediterranean marine energy resources potential

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Document name: **Diagnostic study of the Mediterranean marine energy resources potential**
Document identifier: **D.3.1.2**
Document Class: **Preliminary Study**
Version: **Final**

Project Details:

Programme: **MED INTERREG 2014-2020**

Priority Axis: **1. Promoting Mediterranean innovation capacities to develop smart and sustainable growth**

Objective: **1.1. To increase transnational activity of innovative clusters and networks of key sectors of the MED area**

Project Title: **Promoting innovative nEtworks and cLusters for mArine renewable energy synerGies in mediterranean cOasts and iSlands**

Project Acronym: **PELAGOS**

Project Code No: **1373**

Lead Partner: **CRES**

Total Budget: **2,396,104€**

Time Frame: **1.08.2016-30.04.2019**

Deliverable Details

Component: **WP 3 Studying**

Task Title: **3.1 Capitalizing on and fine-tuning previous experience & knowledge of Blue energy sector in MED**

Deliverable Title: **D.3.1.2 Diagnostic study of the Mediterranean marine energy resources potential.**

Responsible Partner: **HCMR**

Involved Partners: **ENEA, UNIZG FSB, UAlg, CTN, UCV, MARINEM, PMM-TVT (Contribution)**

Date & Place of delivery: **31.01.2017.**

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Contractual Date: **31.01.2017**

# Table of Contents

## List of Figures

# List of Tables

# 1 Purpose of this document

The aim of this deliverable is to collect, review and present the progress as regards the Mediterranean marine energy resources.

The focus of the document is on the estimates of marine renewable energies in two different spatial scales: i) the basin scale, and ii) the regional/local scale. The results presented here are mostly obtained by scientific papers/studies or extended reports from national or European projects relevant to marine energy. Since marine energy is still at an infant stage in the Mediterranean Sea, detailed local analyses regarding offshore wind, wave, tidal/current, thermal or salinity gradients energy are rather scarce.

HCMR undertook the responsibility to collect and process the available literature at the basin scale; almost all types of marine energy sources are estimated in this scale except for current/tidal energy and ocean thermal energy, which depend on the local characteristics of the site of interest to a great extent. The rest project partners provided specific input as regards the aforementioned MRE sources at a national and regional level.

# 2 General Introduction

Energy and climate change policies as well as strategic issues for the decarbonisation of the economy include among others the enhancement and deployment of low carbon technologies such as renewable resources. The recent increasing growth rates of renewable energy sector due to the maturity of renewable energy technologies and the corresponding decrease of their costs, the increase of energy demand and sustainable growth along with the urgent withdrawal from fossil fuels have set marine renewable energy resources a promising alternative solution among the broad range of renewable energy technologies that exists up to date.

Marine renewable energy (MRE) is the energy which can be harnessed from the ocean or the marine wind and it is comprised of five main types according to the origin of the extracted power, namely marine (offshore) wind, surface waves, tides/currents, and thermal and salinity gradients (Bahaj 2011; Borthwick, 2016). Although their growth is relatively slow so far compared to the onshore renewable energy technologies, it is anticipated that MRE will contribute to the energy demands of coastal and insular areas (Esteban & Leary, 2012) and protect and respect at the same time the marine environment.

One of the most exposed regions in terms of climate change and global warming is the Mediterranean Sea (MS). The anticipated sea level rise and the increase in the sea surface temperature may affect a variety of heterogeneous economic activities (e.g. tourism, marine transport, fisheries, etc.) as well as the marine environment (e.g. marine ecosystems) in the future. On the other hand, the particularities that characterize the Mediterranean basin, from the geographical location and demographic pressures to the oceanographic conditions and the intense (and often conflicting) marine and maritime activities, render this region an interesting case study as regards blue growth combined with marine renewables. The development of MRE installations in the MS is, more or less, *terra incognita*, and, to some degree, it is expected to face similar, but probably more intense, problems than those encountered in the northern European Seas (North, Irish and Baltic Seas and the Atlantic Ocean) for various reasons described in the following sections.

Up to now, Europe keeps a leading position in offshore wind power generation, meeting 1.5% of total European electricity consumption by offshore wind (EWEA, 2016), but still remains low (comparing to the onshore wind growth) mainly due to the considerably higher installation and maintenance costs. Offshore wind energy sector seems to be also the most favourable type of renewable energy to be developed in the MS within the next few years mainly because of its technological maturity, commercialization, policy frameworks and installed capacity (Appiott et al., 2014), whereas the rest of MRE are still at an early stage of development, mostly ranging from the conceptual to the prototype phase. Additional motivations for fostering the introduction and consolidation of MRE in the MS is the anticipated increase of share for energy generation from renewable energy resources from 20% in 2020 to, at least, 27% by 2030 according to the EU energy savings targets. Specifically, the European Wind Energy Association (EWEA) and the European Ocean Energy Association (EU-OEA) anticipate that installed capacity for offshore wind and wave/tidal power up to 2020 will reach 40 GW and 3.6 GW, respectively, EWEA (2012).

In the next section, an extended description of the abovementioned MRE sources is provided. Specifically, the main types of MRE are described and the corresponding estimates of each energy source are provided at the Mediterranean level. Section 4 includes estimates of the power potential obtained from these MRE sources based on local/regional case studies. Section 5 summarizes the major findings of this deliverable, while some concluding remarks are also provided.

# 3 Marine Renewable Energies Overview

## *3.1 Offshore wind energy*

### 3.1.1 Introduction

Offshore wind power is generated from the winds blowing over open sea areas. Offshore wind power is currently the most mature MRE source, with potentials for continuous technological advancements (e.g. foundation of wind turbines in deep waters). The majority of the deployed offshore wind farms (OWFs) are based on fixed offshore wind turbines taking advantage the experience gained from the onshore wind turbine installations; for instance, in the first semester of 2016, all the installed offshore wind turbines were based on monopiles and the average water depth of installation was 25 m (https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-mid-year-offshore-statistics-2016-infographic.pdf). However, there are many technical differences between offshore and onshore wind power that should be taken into account during the construction, operation and maintenance (Koh & Ng, 2016).

Furthermore, offshore wind power takes precedence over onshore mainly due to the following features:

- Offshore wind is more consistent and less turbulent than onshore;
- The produced offshore wind power is considerably higher than the onshore (as generally wind speed increases with distance from shore);
- The available space for offshore wind installations is greater than onshore;
- Visual and noise impacts are reduced;
- OWFs may be deployed close to energy demanding/highly populated coastal centres (covering directly their energy needs), where onshore wind energy is more difficult to be developed.

See also Manwell (2013) and Soukissian (2013).

At a global level, in Zheng & Pan (2014), recent estimations suggest that total storage of offshore wind energy across the oceans exceeds $2 \cdot 10^3$ kWh/m$^2$. On the other hand, in Capps & Zender (2010), the offshore wind energy was estimated at the order of $340 \cdot 10^3$ TWh/year, based on satellite (QuikSCAT) observations. At a European level, the installed offshore wind power capacity in the North Sea is 7656.4 MW (69.4%), 1943.2 MW in the Irish Sea (17.6%), 1420.5 MW in the Baltic Sea (12.9%) and 7 MW in the Atlantic Ocean, resulting in a total installed offshore wind capacity for Europe equal to 11027.1 MW, EWEA (2016). The largest number of grid-connected turbines belongs to the UK (1454), followed by Germany (792), Denmark (513) and the Netherlands (184), EWEA (2016).

According to Gaudiosi (1996), the Mediterranean offshore wind energy could be in the same range with onshore wind by 2030, accounting for 5% of the Mediterranean electric energy demand. Notwithstanding the above estimations, a great number of offshore wind projects is still at a concept/early planning stage, while many have been cancelled or remain in a dormant status (http://www.4coffshore.com/windfarms/). Overall, there is no prompt outlook for OWF deployment in the MS.

### 3.1.2 Current estimates of offshore wind energy at the Mediterranean Sea level

The MS is a semi-enclosed basin characterized by various geomorphological and topographical features that influence the wind climatology with strong seasonal and regional variability flows. Local MS winds can be strongly intensified due to channelling effects and interaction with the complex surrounding orography offering thus interesting potential for OWF deployment. Typical regional wind features are shown in **Fig. 1**. For a detailed description of the main Mediterranean winds see Zecchetto & Cappa (2001) and references therein.

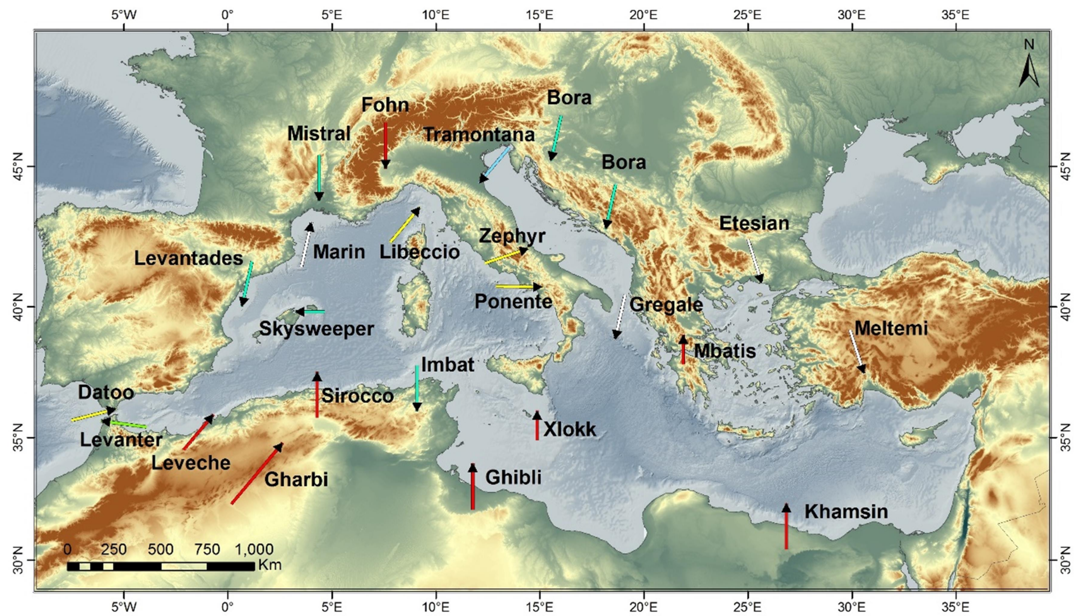


**Fig. 1**: Main winds of the Mediterranean Sea
(Source: CoCoNet project ([1]))

In order to estimate offshore wind power potential for extended spatial scales such as the Mediterranean basin, long-term gridded wind speed data are required. Such data sources include numerical weather prediction (NWP) models (e.g. Soukissian et al., 2008; Tammelin et al., 2013; Hahmann et al., 2014; Menendez et al., 2014), remotely operating instruments (e.g. Furevik et al., 2011; Calaudi et al., 2013) such as radar altimeters, scatterometers, passive microwave radiometers and synthetic aperture radars (SAR), and blending measurements from different satellites through the implementation of appropriate interpolation schemes (e.g. Hasager et al., 2015; Soukissian et al., 2017). For instance, the evaluation of SAR for offshore wind mapping in the MS was performed by Calaudi et al. (2013). The obtained results revealed consistency between SAR-based spatial wind variability and previous studies. The available offshore wind power potential over the MS was also estimated in the work of Menendez et al. (2014) based on a dynamical downscaling of the ERA-Interim reanalysis dataset, performed at 15-km horizontal resolution for 20 years.

([1]) Part of these results has been produced in the context of the project "Towards COast to COast NETworks of marine protected areas (from the shore to the high and deep sea), coupled with sea-based wind energy potential" (CoCoNET), that has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 287844; see http://www.coconet-fp7.eu/. Hereafter, this project will be referred to as CoCoNET. HCMR was the leader of Work Package 5 "Offshore wind farms and Marine Protected Areas". In the context of this work package the Smart Wind Chart for the Mediterranean has been produced (http://coconetgis.ismar.cnr.it/).

A recent analysis of wind speed and wind energy density over the MS was conducted by Balog et al. (2016), leading to the selection of certain potentially suitable sites for wind energy applications. However, their approach does not take into account bottom depth, which is a major technical restriction; see also **Fig. 4** below. An offshore wind potential assessment in the Mediterranean, taking into account bottom depth restrictions, has been also recently performed by Soukissian et al. (2017) using the Blended SeaWinds (BSW) satellite dataset, obtained from the US National Oceanic and Atmospheric Administration (NOAA), covering the period 1995–2011.

An in-depth assessment of the offshore wind power potential in the Mediterranean basin has been performed in the recently completed CoCoNET project; see http://www.coconet-fp7.eu/. In the context of the CoCoNET, three different wind data sources were thoroughly analysed:

- satellite data from the Blended SeaWinds product of the NOAA with 6-hour sampling frequency, spatial resolution 0.25°×0.25° and time period 17 years (1995–2011);
- ERA-Interim reanalysis data, Dee et al. (2011), with 6-hour sampling frequency, spatial resolution 0.25°×0.25° and time period 33 years (1979–2011);
- SKIRON-Eta atmospheric model results, Papadopoulos et al. (2011), with 3-hour sampling frequency, spatial resolution 0.1°×0.1° and time period 15 years (1995–2009). Clearly, SKIRON-Eta model results are characterized by the highest spatial and temporal resolution.

The above datasets have been validated by using *in situ* measurements from oceanographic buoys and coastal meteorological stations. As regards the estimated offshore wind power potential, the analysis revealed uncertainties, which are related with the different sources of data sets, the different spatial resolution and the sensitivity of the satellite data near the land-sea boundary. Another project that has analysed offshore wind energy in the MS is the ORECCA project (http://www.orecca.eu/project).

In **Fig. 2**, the mean annual wind climate in the MS obtained by hindcast model data is depicted. According to these results the Mediterranean wind pattern presents several localized extremes, such as the Gulf of Lions (France) and the central Aegean Sea (mean annual wind speed of the order of 8 m/s), and the Kasos Straits (Greece). The highest mean annual variability is exhibited in the northern part of the Adriatic Sea, and then the Ligurian Sea, the Tyrrhenian Sea (especially offshore the northern coasts of Sicily), the N. Aegean Sea, the Gulf of Antalya and the Balearic Sea (between Palma de Mallorca, Ibiza and the eastern coasts of Spain). The highest inter-annual variability appears near the coasts of Monaco and then in the N. Adriatic, Tyrrhenian and Balearic Seas, the Gulf of Lions, the coasts of Algeria, the Ionian and the central Aegean Sea.

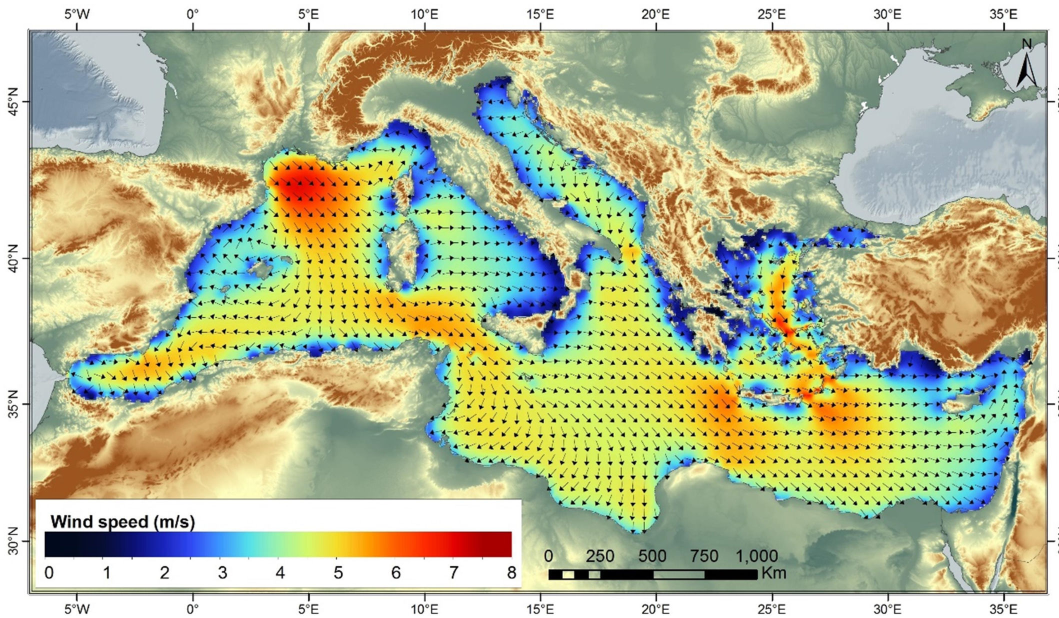


**Fig. 2**: Mean annual wind climate (at 10 m above sea level) in the Mediterranean Sea according to the SKIRON-Eta model. Arrows indicate the mean annual wind directions (Source: CoCoNET project).

Since a long time series of wind speed at the model grid points is available, the wind power density $\overline{P}$ (W/m$^2$) can be estimated directly at these grid points by applying the following equation:

$$\overline{P} = \frac{1}{2N}\sum_{i=1}^{N} \rho u_{80,i}^{3}, \qquad (1)$$

where $N$ is the total sample size of the wind speed time series, $\rho$ is the air density, considered to be constant and equal to 1.2258 kg/m$^3$, and $u_{80,i}$ is the value of wind speed obtained from the corresponding time series. The wind speed provided at 80 m height above sea level (asl), roughly corresponding to the turbine hub height, was estimated by applying the log-law:

$$u_{80} = u_{10}\frac{ln(h/z_0)}{ln(10/z_0)}, \qquad (2)$$

where $u_{80}$ is the wind speed at the examined level (i.e. 80 m asl), $u_{10}$ is the wind speed at 10 m asl (obtained from the NWP model results) and $z_0$ is the roughness length that equals to 0.001 m for open sea areas (Hansen, 1993). Without doubt, the accurate description of the wind climate in an area is a rather delicate issue, since rather small variations of $u$ (corresponding to the actual value of $u$, if wind speed measurements were available) lead to very large variations in $\overline{P}$ due to the third power. The mean annual offshore wind power density in the MS is presented in **Fig. 3**.

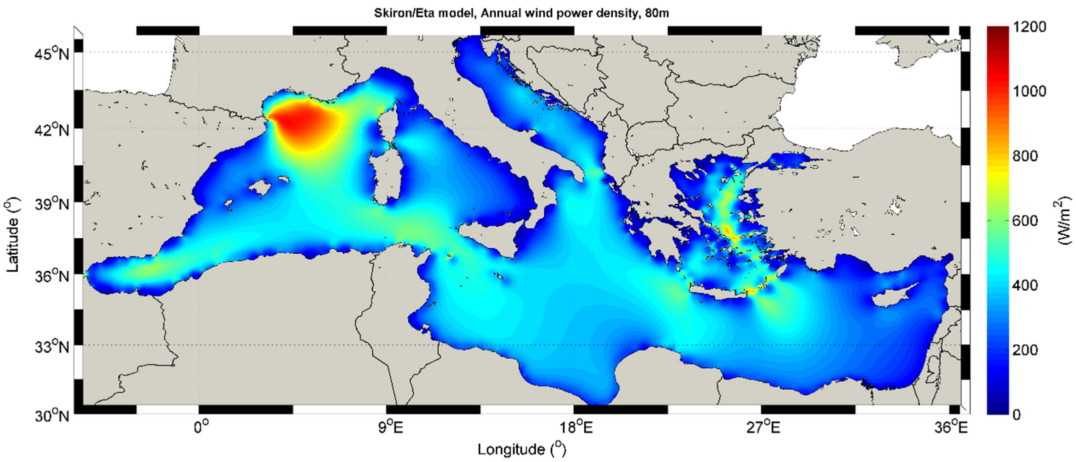


**Fig. 3**: Mean annual offshore wind power density at 80m height asl according to the SKIRON-Eta model (Source: CoCoNET project)

The obtained spatial distribution of wind power potential in this figure suggest that the highest annual mean power density (approximately 1050 W/m$^2$) is depicted in the Gulf of Lions, followed by the central Aegean Sea with a mean annual power density up to 890 W/m$^2$. High offshore wind resource is also found in the offshore areas east and west of the Crete Island, east of the Gibraltar Strait, in the western Ligurian Sea, in the Strait of Sicily and in the Otranto strait.

In **Fig. 4**, candidate locations for potential OWF development in the MS are depicted. The main criteria for the selection are the mean annual wind speed (greater than 4.1 m/s at 10 m height asl) and the bottom depth suitability. Let us note that this (rather low) wind speed limit was chosen since it was shown that SKIRON-Eta model underestimates (sometimes significantly) high values of wind speed, Soukissian & Papadopoulos (2015). Three different scenarios as regards water depths are considered: “shallow waters” with depths between 0–40 m, “intermediate waters” with depths between 40–70 m and “deep waters” with depths between 70–200 m.

From this figure, it can be concluded that a large part of the Adriatic Sea and the Gulf of Gabes are favourable for OWF development as regards all considered water depths. Other areas that seem to be prominent for OWF development are the Aegean Sea, the Gulf of Lions, along the Mediterranean coasts of Spain, as well as along and off the North African coasts (especially off the Nile river estuary). Nevertheless, in real-world applications, additional parameters (environmental, socio-economic, financial, etc.) should be taken into consideration during the selection of candidate locations for OWF development. In this line, another major outcome of the CoCoNET project is the production of the “Smart Wind Chart”, i.e. of a multi-parameter tool for the pre-evaluation of potential locations in the Mediterranean and Black Sea basins as regards prospects of OWF development. A site-specific application of the Smart Wind Chart in the MS (Othoni Isl. in northern Ionian Sea) can be found in Soukissian et al. (2016).

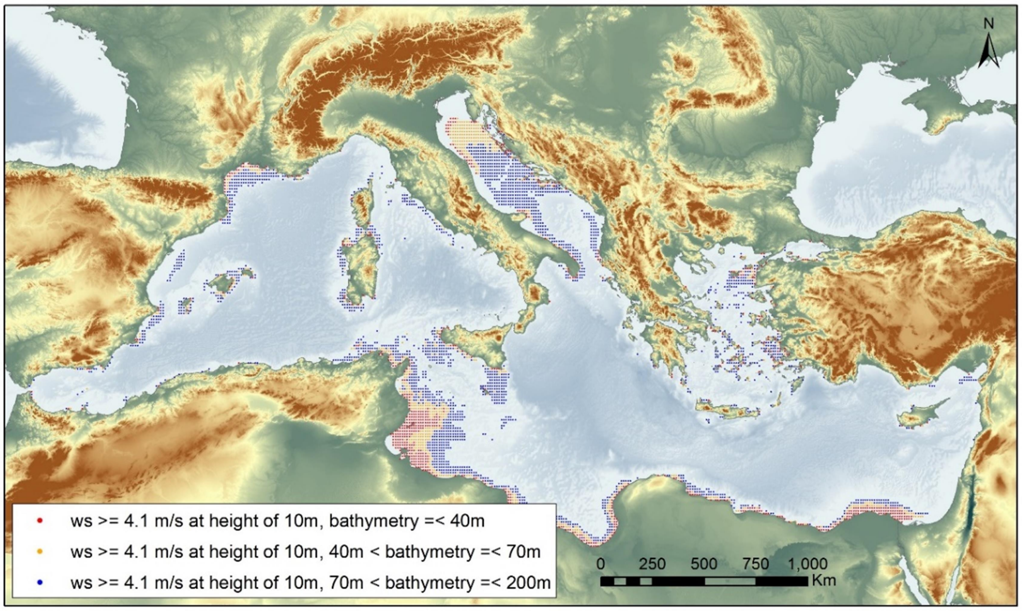


**Fig. 4**: Potential hot-spots for OWF development in the Mediterranean Sea
(Source: COCONET project)

In the recent study of Koletsis et al. (2016), the potential impact of climate change on wind energy in the Mediterranean basin was analysed thoroughly based on global climate change scenarios and data from the EU-funded ENSEMBLES project. According to the consensus rate, an adopted measure for the identification of the areas over the MS where all the examined regional climate model simulations (i.e. constituting the ensemble members) show an overall agreement, wind power is projected to increase more than 5% over the Aegean Sea and expected to decrease more than 5% over the maritime areas of North Africa and Middle East for the period 2021–2050. Regarding the period 2061–2090, an increase of wind power is expected over a large part of the Aegean Sea as well as over the western edge of Alboran Sea (nearby Gibraltar Strait), while a decrease exceeding 5% over a large part of the central and easternmost Mediterranean Sea is also anticipated.

Finally, an assessment of climate variability and climate change in the Mediterranean region for different variables, including wind, was made in the context of the FP-7 project CLIMRUN. During the first phase of CLIMRUN, wind fields were identified as a key climate variable of interest for the case studies on energy (Morocco, Spain), and the need for more in-depth understanding of wind modelling capacities at a longer time scale was highlighted, which may contribute to both site evaluation and the risk assessments that may affect the return on investments on longer time scale. The evaluation of wind modelling was performed in the context of the consolidated ensemble of RCMs produced during the EU-FP6 ENSEMBLES RCMs simulations over Euro-Mediterranean region, both for present climate and future scenarios; see Bellucci et al. (2013).

Other recent relevant analyses including the examined basin can be found in Onea et al. (2016), Reyers et al. (2016) and Carvalho et al. (2017).

## 3.2 Current/tidal energy

### 3.2.1 Introduction

Tidal energy is the hydrokinetic energy that can be extracted either from the sea level fluctuations due to tidal range or from tidal-driven currents, Bryden (2013). Kinetic energy from current flow can be extracted by tidal energy devices that, in turn, actuate a rotor or foil. Then, this mechanical motion can be converted to electricity thanks to a power take-off mechanism. In comparison with offshore wind energy, tidal energy is a high-density energy form while it is also characterized by high predictability (their variability is deterministic, since tides result from gravitational forces). The global estimations of tidal energy potential is approximately 3 TW, while 1 TW is technically exploitable, IRENA (2014d).

Significant tidal ranges or current velocities occur only in certain locations. Flow velocities are generally determined by the bathymetry, the seabed roughness and the surrounding land mass topography. The largest tidal range can be usually found in estuaries that show resonant behaviour. Examples of such locations in Europe can be found in Severn Estuary (in the UK) with mean tidal range 7.0 m, and La Rance (in France), with mean tidal range 8.5 m; the latter location is considered one of the world's largest tidal barrage with total installed capacity 240 MW; see also Borthwick (2016).

Installation and grid-connection of tidal-stream energy converters (TECs) has taken place in several locations in Europe. The UK, Denmark, France, Germany, Ireland, Italy, the Netherlands, Norway, Sweden and Spain have been involved in the tidal energy sector. Northern European Seas have a significant tidal energy potential, while the UK and France have the greatest resource, Ernst & Young (2013). The first full-scale prototype tidal energy turbine (with maximum power capacity of 300 kW) was installed in 2003 in the UK (Seaflow prototype). In 2012, European Marine Energy Centre (EMEC) installed five tidal devices (4 MW) in the UK waters for testing. Prototypes for testing have also been installed in Italy and Norway, while a tidal energy farm of 2 MW has been started testing since January 2013 in France, Ernst & Young (2013). On March 2015, a tidal floating platform (200 kW) was demonstrated in the Netherlands (http://tidalenergytoday.com/2015/07/07/plat-o-tidal-turbines-platform-up-and-running/). According to Sgobbi et al. (2016), tidal energy could be deployed in 2030 provided that major technology improvements are achieved (e.g. at least 50% cost reductions).

Over the last ten years, numerous technologies of TECs have been proposed, focusing on diverse concepts (e.g. floating TECs, small-scale TECs, multi-turbine platforms, etc.), but they are still in the concept/planning phase. Although this plethora sounds overwhelming, however, coupled with the limited financial resources, may hold back the commercialization of the TECs (Bahaj, 2011).

### 3.2.2 Current estimates of current/tidal energy at the Mediterranean Sea level

Tidal energy resource in the MS is very low compared to other areas of the world, where tidal energy sector is already under development (e.g. the UK, France, Norway, etc.). In the Mediterranean basin there is no commercial development of the tidal energy sector. As tidal turbines need a stream speed of at least 1.5–2 m/s in order to be effectively operating, tidal energy potential of the basin sets specific constraints with the current technological status of TECs. As a consequence, up to now, there is no commercial development of the tidal energy sector in the Mediterranean basin; however, developers have started studying TECs that could exploit slow tidal flows during the past few years (Magagna & Uihlein, 2015), which may be an alternative solution for the Mediterranean waters.

Based on the current speed limits provided above, very few Mediterranean sites could be of particular interest. The straits of Dardanelles, Gibraltar and, particularly, the strait of Messina (where tidal stream energy resource presents its highest values) are exceptions that have been under consideration. However, further research is essential, since only preliminary/basic studies have been conducted regarding the energy potential sufficiency of these areas. For example, a recent estimation of marine current energy fluxes in the Gibraltar Strait was conducted by Calero Quesada et al. (2014) revealing the suitability of certain spots for a power plant installation. Computed averaged fluxes in these locations of the strait can exceed 1.8 kW/m$^2$. See also Section 4.2, where all relevant regional/local studies are presented.

Let us note that if measurements of tidal currents are available, then the tidal power density is analogous to Eq. (1), where air density and wind speed are replaced by water density and current speed, respectively.

## 3.3 Wave energy

### 3.3.1 Introduction

Wave energy is the marine hydrokinetic energy that can be harvested from the motion of ocean waves. As wind energy is transferred to the sea surface through air-sea interaction processes, sea surface waves are generated. Evidently, wave energy highly depends on wind characteristics (wind speed, fetch length, duration), since they determine in great extent the most important wave characteristics (significant wave height, energy period). Several advantages are attributed to this type of energy, Clément et al. (2002):

- waves present the highest energy density among other MRE sources;
- energy losses are small even for long distances of wave propagation in the form of swell,
- wave energy devices can have minimal visual impacts, since some types can be entirely submerged under water,
- wave energy is more persistent "*with less potential for sudden changes in the resource potential*" (IRENA, 2014a), and;
- seasonal variability of wave energy resource and electricity demand in temperate climates are highly correlated.

On the other hand, various hydrodynamic processes caused by wave phenomena, such as diffraction and radiation, IRENA (2014e), complicate the exploitation of wave energy conversion into electrical power, adding technical and economic challenges. Furthermore, wave predictability is associated with great errors and uncertainties since it is based on wind predictability while large random variability is evident in several time scales (Clément et al., 2002; Falcão, 2010). Wave energy is more spatially concentrated compared with offshore wind energy Falnes (2007).

Global wave power resource has been estimated based on various wave data sources by Mørk et al. (2010) (around 3700 GW), Arinaga & Cheung (2012) and Reguero et al. (2015) (32000 TWh/year). Although based on rather short length time series of spectral parameters, an interesting and very detailed work as regards the estimation of the global wave resource is made by Gunn & Stock-Williams (2012). See also the reference list provided there.

To date, there are more than 100 wave energy projects under various development stages, involving over 30 countries across the globe; see Bahaj (2011), IRENA (2014e). As regards Europe, it keeps the leading role in wave energy development. The first grid-connected commercial scale wave energy device was Islay Limpet in 2000 (500 kW, Scotland), two wave energy converter (WEC) prototypes were deployed in the UK (Pelamis, 750 kW) and Portugal (Archimedes Wave Swing, 2 MW - http://awsocean.com/technology/archimedes-waveswing-submerged-wave-power-buoy/), while the first wave energy project was the Aguçadoura wave farm in 2008 (2.25 MW total capacity, Portugal) installed by Pelamis Wave Power. In 2011, a commercial wave plant started operating in Spain (Mutriku) with 296 kW of total capacity. Europe's first grid connected wave energy array launched in 2016 (in Gibraltar, developed by Israeli Eco Wave Power), supplying 100KW with an expansion plan to 1–5 MW.

### 3.3.2 Current estimates of wave energy at the Mediterranean Sea level

The limited fetch lengths in the MS prevent waves from travelling for long distances without large dissipation (swell), generating in this way smaller (short-crested) waves compared to the Atlantic Sea. When both strong winds and long fetch exist simultaneously, then higher values of significant wave heights are observed. The most effective combination of the above features is met in the western Mediterranean and the Ionian Sea. Despite the limited fetch lengths, measurements obtained from moored buoys in the MS, as well as numerical modelling results, reveal the existence of sea states with significant wave height between 5 and 7 m, or even up to 10–11 m in case of extreme storms.

The available wave energy flux per unit crest $P$ (W/m) for a particular sea-state can be estimated by applying the following equation:

$$P = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e, \qquad (3)$$

where $\rho$ denotes the water density (1025 kg/m$^3$), $g$ the gravity acceleration (9.81 m/s$^2$), $H_{m0}$ and $T_e$ is the significant wave height and the wave energy period, respectively, defined from the -1 and zero-th order spectral moments.

The spatial distribution of offshore mean annual wave power and wave direction in the MS is depicted in **Fig. 5**. The results have been derived by HCMR using time series of wave spectral parameters for the period 1979–2013 from the ERA-Interim database, obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF), Dee et al. (2011). The highest annual wave energy potential is depicted in the extended area between Sardinia and Balearic Islands (values up to 9.4 kW/m). The estimated mean annual wave energy potential in the offshore southwestern part of Crete Isl. is of the order of 5.8 kW/m, while the Levantine and the Ionian basin, the area between Tunisia and Sicily, and the central and northern Aegean Sea present steady wave energy potential in the mean annual scale.

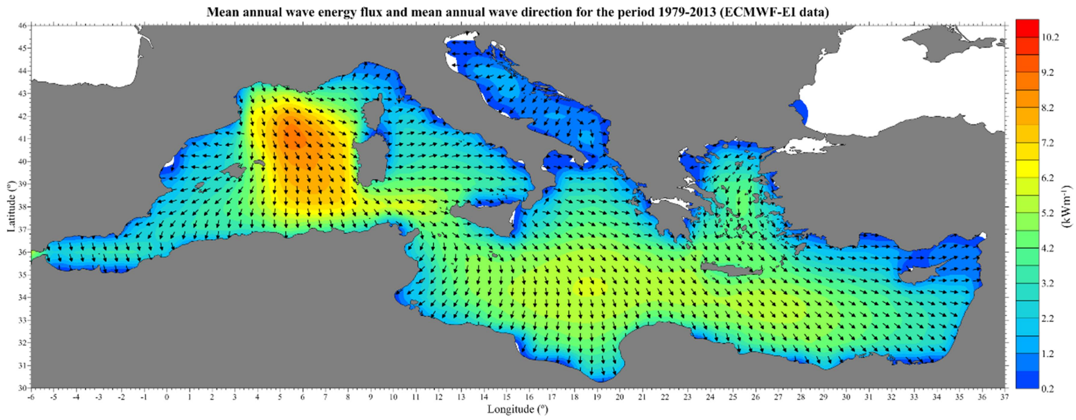


**Fig. 5**: Mean annual wave energy flux and mean wave direction in the Mediterranean Sea obtained from ERA-Interim database, 1979–2013

From the above-mentioned values of wave energy potential in the MS, it is evident that wave energy is remarkably smaller when compared with the northern and western European locations that already have adopted wave harnessing approaches close to the commercial stage. For instance, in the North Sea, wave power ranges within 10–60 kW/m while in front of the northern French and Portuguese coasts the annual wave energy values vary from 30 to 50 kW/m, Beels et al. (2007). However, in Vannucchi & Cappietti (2016), it was stated that the exploitation of wave energy in the MS is facilitated by the fact that the current wave technologies can efficiently harvest wave energy potential because of the wave conditions.

Other studies based on wave energy estimation in the examined basin can be found in Liberti et al. (2013), and Besio et al. (2016). Specifically, in Liberti et al. (2013) the wave energy resource was estimated based on a third generation ocean wave model for a 10-year period (2001–2010) at a resolution of 1/16°. The model was first validated against buoy measurements and satellite data while the simulation results revealed that the most energetic waves are located in the western part of the basin, in the area between the Balearic Isl. and the western coast of Sardinia. Another detailed wave resource assessment for the entire MS was performed by Besio et al. (2016). It was based on long-term (35 years) high temporal and spatial resolution numerical wave model results. The authors concluded that the most wave energetic area is located between the Balearic Islands, Sardinia and Corsica and the northern coast of Algeria, while central and eastern MS present moderate wave energy potential with mean value around 6−7 kW/m.

On the other hand, specific locations of the MS (with high energetic contribution) were examined in terms of wave climate conditions by Arena et al. (2015) while the main aim of the study was to identify particular aspects relevant to the design of wave energy harvesters. In the same study, the significance of the directional pattern of sea-states was also highlighted since it affects sea-state statistics and therefore wave energy harvesters designing; see also Soukissian (2014). Another study in a rather extended area of the MS, the Levantine basin, was conducted by Zodiatis et al. (2014), who studied wave energy potential based on high resolution wind-wave numerical models from a 10-year database. The obtained results showed that the highest energy potential values are met off the western and southern coastlines of Cyprus, the sea area of Lebanon and Israel and the coastline of Egypt around Alexandria. Despite the relatively low values of wave energy potential over these areas, it is claimed that wave energy is exploitable due to the stable behaviour of wave power values in an annual basis.

## 3.4 Ocean thermal energy conversion and salinity gradients

### 3.4.1 Introduction

Ocean thermal energy conversion (OTEC) is the technology that harnesses indirectly solar energy by taking advantage of the temperature differences between the surface and subsurface of oceans. OTEC power generation requires a temperature difference of at least 20°C; such temperature differences between surface and deep layers can be found at tropical latitudes, where the typical thermocline depth is about 1 km. However, in the MS temperature differences of this order of magnitude can never be reached, not even between surface and sea bottom.

The main advantages of OTECs are summarized below (Edenhofer et al., 2011):

- large scale potential;
- continuous energy supply with small variations (daily and seasonal);
- production of fresh water apart from electricity, and;
- possibility of cooling without electricity consumption.

OTECs can be land-based, sea-based, or fixed on floating platforms. Considering the operational concept of the existing convertors, there are three separate technology categories; see e.g. Vega (2013), Kim et al. (2016):

- the open-cycle OTEC;
- the closed-cycle OTEC, and;
- the hybrid systems.

Despite OTEC technology tests dating back to the 1930's, large scale projects have not been implemented yet mainly due to the harsh marine environment conditions; on the other hand, large scale OTEC systems are necessary, because small temperature differences demand very large volumes of water IRENA (2014b). The largest OTEC project ever built is still the 1 MW plant located in Hawaii, which operated from 1993 to 1998. Currently, several projects (up to 10 MW) are under development, while concepts and prototypes concerning many countries around the world are currently being explored. The most active countries in OTEC sector is China, Curacao, Malaysia, Oman, Philippines, South Korea, the USA (Hawaii, Guam, Puerto Rico), and Zanzibar (Edenhofer et al., 2011) while, in general, most of the European waters may not be suitable for this type of ocean energy.

At a global scale, OTEC has a theoretically available energy potential of the order of 44000 TWh/year, Nihous (2007), Rajagopalan & Nihous (2013). However, this amount is practically very limited due to the implications that may be caused on the oceanic thermal structure. The same authors claim that an annual OTEC power production of the order of 7 TW could be achieved without significant effects on the temperature field of oceans.

Salinity gradient energy (or osmotic power) is based on the difference in salinity between fresh (river) water and salt (sea) water. The principle behind this type of energy is that fluids with different salinity concentration tend to diffuse until their chemical composition is evenly distributed; electricity can be extracted from this tendency for mixing by the two heterogeneous fluids, Alvarez-Silva et al. (2014). For this reason, the most suitable locations for salinity gradient power are the ones where rivers end up to the sea.

The salinity of surface waters depends mainly on the difference between the evaporation and precipitation. Other less important factors are freezing and sea ice melt. In areas of high evaporation, such as the Red Sea, the salinity can be as high as 40 psu. However, in the majority of the seas, the salinity range varies between 33 and 37 psu, with an average value of 35 psu. The highest values of salinity occur near arid tropical areas while the lowest values occur near polar regions.

Globally, the exploitable potential from salinity gradients is estimated around 5177 TWh; however, exclusion of environmental and legal parameters may have overestimated this value, IRENA (2014c). According to a more recent and detailed study by Alvarez-Silva et al. (2016), the globally extractable energy from river mouths is 625 TWh/year, equivalent to 3% of global electricity consumption.

The first prototype osmotic power device was developed in Norway by Statkraft and became operational in 2009 with 10 kW capacity (Nijmeijer & Metz, 2010; Edenhofer et al., 2011), but in 2013 the company terminated its plans for further development and research due to the low cost efficiency of osmotic power technology.

At present, in the European territory, pilot projects exist in Norway and the Netherlands, while research projects have started in Germany and Italy. Recent developments in membrane technologies, aiming in cost reductions, has led to an increasing interest in the sector with expectations to enter the commercial phase around 2020; Willemse (2007), Nijmeijer & Metz (2010), Edenhofer et al. (2011), IRENA (2014c).

### 3.4.2 Current estimates of salinity and thermal gradient energy at the Mediterranean Sea level

Characteristics of the sea surface layer are modified constantly due to mixing processes. In general, the following features are present in the MS:

- Surface temperature is higher in the eastern part of the basin compared to the western. The Ionian Sea and the Levantine basin are characterized by the warmest surface waters (19.5–21°C and 20–22°C, respectively) while the Gulf of Lions is characterized by the coldest (17–19°C), Romanou et al. (2010).
- The intermediate layer, which lies between 200 and 800 m, has varying temperatures from 13°C to 15.5°C.
- The deep layer, which covers the depths between the intermediate layer and the bottom, has a temperature in the order of 12.7°C in the Western Mediterranean Deep Water, and 13.6°C in the corresponding eastern part, UNEP (2012).

In order to estimate ocean thermal power density, various parameters are involved, i.e. heat capacity of seawater, turbo-generator efficiency, temperature difference between warm and cold water for the plant, pipe loss/fractional energy loss to cold water pumping and warm water intake temperature for OTEC. Since the above parameters are site-dependent, it is not feasible to provide general estimates for ocean thermal energy availability in the spatial scale of the MS; see also Nihous (2005). Moreover, mean temperature vertical profiles of the MS do not meet the necessary requirements for an efficient exploitation of the resource, as stated in the introduction above. For the Mediterranean waters, an alternative solution was proposed by Georgiou et al. (2012) in terms of OTECs; the exploitation of the temperature difference between the atmosphere and the sea water may be feasible as it is analogous to the water temperature differences at a tropical location.

At a global level, a detailed assessment of salinity gradient energy potential, along with the identification of locations with utilizable resource, is presented in Alvarez-Silva et al. (2016). According to this study, specific river mouths of the Mediterranean coasts have been identified as promising candidates for salinity gradient energy utilization.

The spatial distribution of mean annual surface salinity in the Mediterranean basin for the period 1987–2013 obtained from the Mediterranean Forecasting System reanalysis (http://marine.copernicus.eu/) is presented in **Fig. 6**. It is evident that the eastern sub-basin (i.e. Levantine basin, central and southern Aegean Sea and part of the Ionian Sea) is characterized by the highest values of mean annual surface salinity (above 38.5 psu) while the lowest values (around 35 psu) are depicted in the northern Aegean and Adriatic Seas. On the other hand, the low salinity zones that can be recognized in **Fig. 6** are due to the following features: i) the Po discharge in Adriatic Sea and ii) the Black Sea input which acts as a river, due to its low salinity with respect to that of the Aegean Sea. Also Rhone and Ebro discharges can be recognized in the map. These low salinity zones could be used as primary candidate locations for any future deployment of relevant devices.

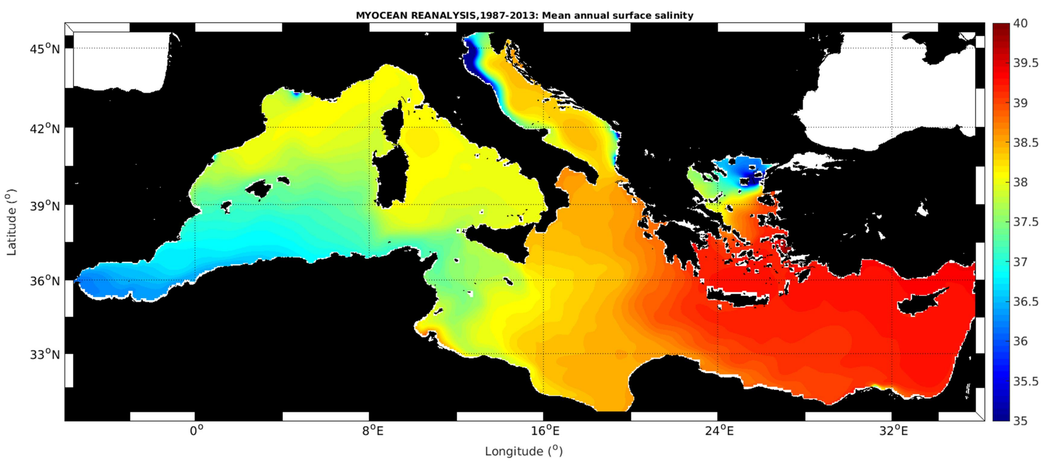


**Fig. 6**: Mean annual surface salinity in the Mediterranean Sea
(data obtained from http://marine.copernicus.eu/)

# 4 Marine Renewable Energies at the Local/Regional Level of the Mediterranean Sea

In this section, analytical studies, which are confined in the spatial scale (referring to a national or regional level) are reviewed and presented for some European Mediterranean countries as regards the above-mentioned types of blue energy.

## *4.1 Current estimates of offshore wind energy at local/regional scales of the Mediterranean basin*

### 4.1.1 Greece

Regarding the wind climate of the Aegean and Ionian Seas, the mean annual offshore wind speed and direction (at 10 m asl) are presented in **Fig. 7** ([2]). It is noticed that the winds blow from the north-eastern directions for the N. Aegean Sea, while the north-western directions are the most characteristic in the Ionian Sea (western part of Greece). At the western part of the Levantine Basin the wind blows in the mean from the west-northwest directions. As regards the mean annual wind speed at the reference level of 10 m asl, the maximum value is observed at the central Aegean Sea between Mykonos and Ikaria Isl. reaching the value of 7.57 m/s. A gross comparison of the Aegean and Ionian Seas reveals that the Aegean is clearly windier.

From the examination of wind speed pattern at the seasonal time scale (figures are not presented here), it is concluded that summer wind speeds are characterized by the highest values with maximum value around 9 m/s between Karpathos and Kasos Isl., then winter follows with maximum value up to approximately 8 m/s at N. Aegean Sea, between Agios Efstratios and Lesvos Isl., then autumn with maximum value up to 7.35 m/s at the central part of the Aegean Sea, and finally, spring with maximum value up to 7.03 m/s at the E. Aegean Sea between Ikaria and Samos Isl.

The overall windiest month for the Aegean Sea is February and then December and January follow. However, the largest monthly values of wind speed are observed during July and August. The largest mean monthly value of wind speed (9.80 m/s) is observed during July at Karpathian Sea, and the second largest (9.0 m/s) during August at the same area.

In **Fig. 8**, the offshore wind power density is presented at 80 m height asl for the annual scale. The highest value of the mean annual wind power density is depicted in the eastern part of the Aegean Sea with value ~885 W/m$^2$, while the lowest value (~21 W/m$^2$) is depicted at the north-western part of the Aegean Sea. The behaviour of wind power density at the seasonal scale (figures are not presented here) can be described as follows: the highest value is observed during summer reaching peak values around 1172 W/m$^2$ at the south-eastern Aegean Sea; winter follows with highest value ~1090 W/m$^2$ at the northern Aegean Sea, then autumn with peak value ~806 W/m$^2$ at the central part of the Aegean Sea, and finally, spring with peak value ~773 W/m$^2$ at the eastern Aegean Sea. In the Ionian Sea, the wind power density reaches values up to ~584 W/m$^2$ at the northern part and ~490 W/m$^2$ at the southern part. During winter, the corresponding maximum

([2]) Part of the results presented for Greece has been produced in the context of the project "National programme for the utilization of offshore wind potential in the Aegean Sea: preparatory actions" (AVRA), that has been funded from the Greek General Secretariat for Research and Technology and the European Regional Development Fund under Grant Agreement no. 09SYN-32-598. Hereafter, this project will be simply referred to as AVRA. These results have been submitted for publication in the international open access journal *AIMS Energy*.

wind power density values are ~790 W/m$^2$ and ~780 W/m$^2$. Overall, the lowest values of wind power density in the Ionian Sea are observed during summer.

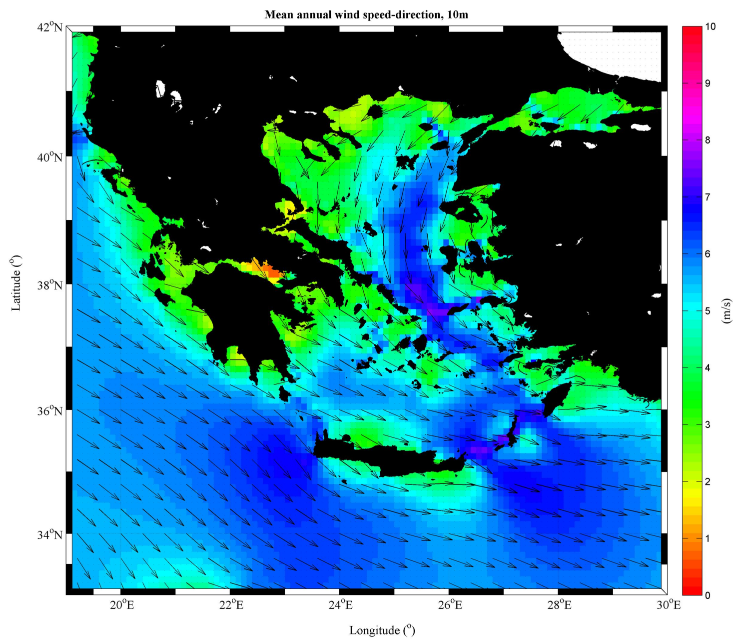


**Fig. 7**: Spatial distribution of mean annual offshore wind speed and wind direction at 10 m height asl in the Aegean and Ionian Seas for the period 1995–2009
(Source: AVRA Project)

Overall, it seems that the wind potential mainly in the Aegean and then in the Ionian Sea is adequately exploitable at specific locations, while the current maturity of offshore wind industry is appropriate to expand in these areas.

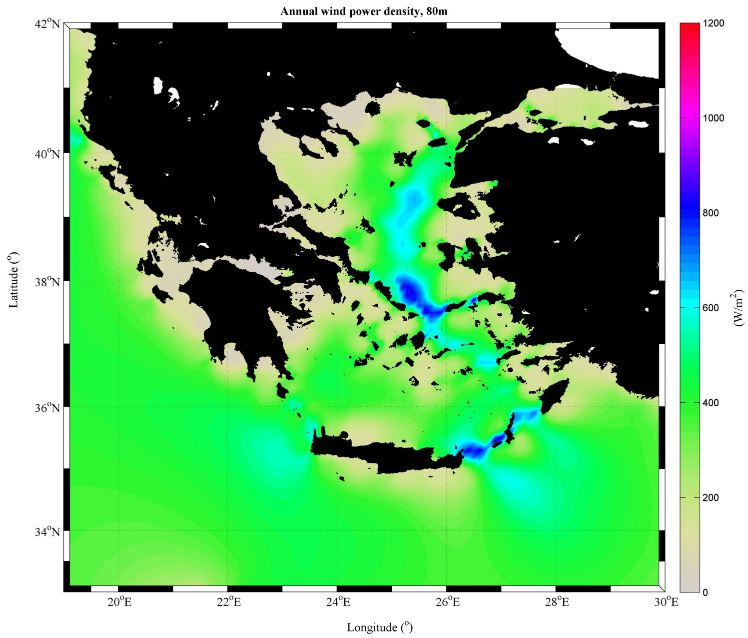


**Fig. 8**: Spatial distribution of (a) mean annual offshore wind power density, (b) mean offshore wind power density in winter, (c) spring, (d) summer and (e) autumn, at 80 m height asl in the Aegean and Ionian Seas for the period 1995–2009
(Source: AVRA Project)

Others studies related to offshore wind energy assessment that are referred to either Greece or Greek regions are the following:

- Soukissian et al. (2012), where the offshore wind (and wave) potential of the Greek Seas was analysed from *in situ* measurements of varying recording periods;
- Soukissian et al. (2016), where an analytic feasibility study as regards OWF development in the Othoni Isl. (northern part of Corfu Isl.-western Greece) was presented;
- Bagiorgas et al. (2016), where the wind power potential was examined at three buoy locations in the Ionian Sea;
- Zafeiratou et al. (2016), where offshore wind energy was analysed in the northern Aegean Sea from the techno-economic perspective;
- Giannaros et al. (2017), where simulated wind speeds from 1-year period model results were used to estimate wind resource, represented by the Weibull probability density function, over Greece.

### 4.1.2 Croatia

Until now there are no wind velocity measurements at offshore sites along the Croatian coasts. The presented numerical results for mean annual wind velocities and wind power density should be treated with some caution since they are the output of the numerical atmospheric model ALADIN and represent the average values within the 2 km x 2 km grid box. The local wind speed at a particular location may be lower or higher than the average grid area value (http://meteo.hr/index_en.php).

In **Fig. 9** the spatial distribution of the mean annual wind velocity at 10 m height asl is presented over Croatia. In general, the highest energy extraction efficiency is achieved for wind velocity between 5 and 25 m/s. According to this figure, the sea areas of Croatia are characterized by moderate winds (5–6 m/s) while in the northern coasts, some particular locations (between Cres and Krk Isl., and eastern coasts of Pag Isl.) have relatively higher winds, but they are close to the Croatian coasts.

The corresponding spatial distribution of the mean annual wind power density at 10 m height asl is shown in **Fig. 10**. High values of wind power density at this reference level are up to 450 W/m$^2$.

In **Fig. 11** the mean annual wind velocity at 80 m height asl is presented. As the energy potential of a particular wind turbine is usually determined based on the mean wind velocity value at the hub height, the results of **Fig. 11** can be considered for estimating the mean wind velocity for offshore wind turbines on the Croatian Adriatic maritime region. From this figure the mean annual offshore wind speed ranges from 5.5 to 6.5 m/s, which is fair for power production. At the open sea, it can be seen that the highest mean wind velocity is between Pula and Lošinj Isl. at the north, close to Šibenik in the middle part of Croatian Adriatic area, and south of Mljet Isl.

An important problem in the Croatian part of the Adriatic Sea that needs to be specially considered is the strong and gusty Bora wind developing at rather high and steep coastal mountains like Velebit and Biokovo. This is evident in **Fig. 11**, where the highest mean annual velocity is present. Bora's mean wind velocity is rarely higher than 17 m/s, however it has wind gusts reaching values up to 70 m/s (Liščić et al., 2014). In **Fig. 12**, the spatial distribution of mean annual wind power density at 80 m height asl is presented.

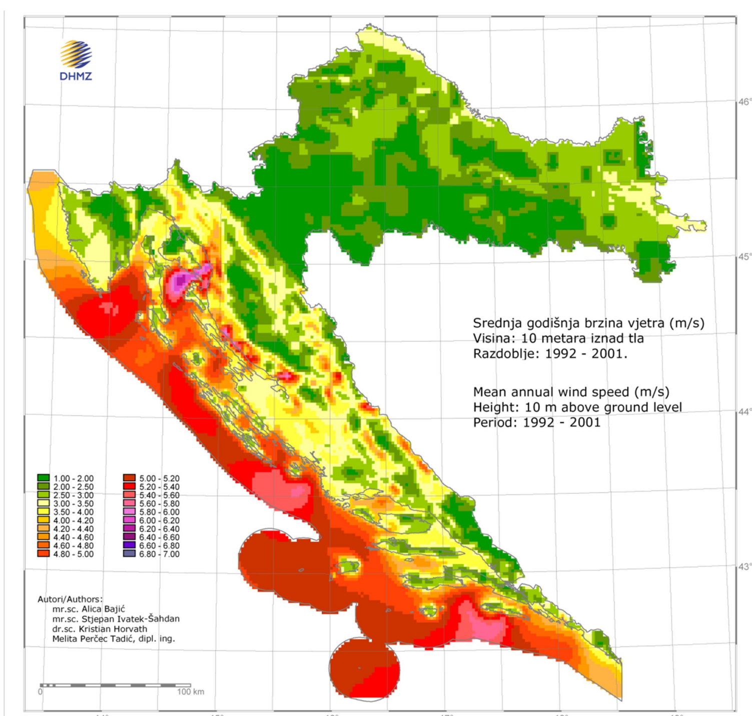


**Fig. 9**: Mean annual wind velocity at 10 m height asl
(Source: http://meteo.hr/index_en.php)

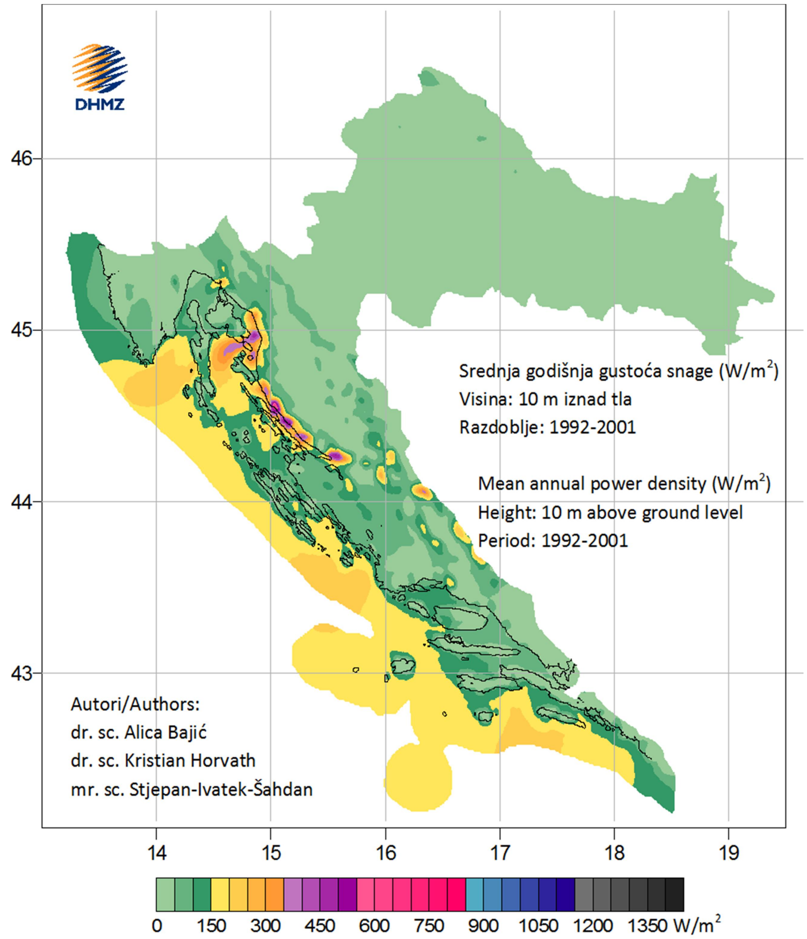


**Fig. 10**: Mean annual power density at 10 m height
(Source: http://meteo.hr/index_en.php)

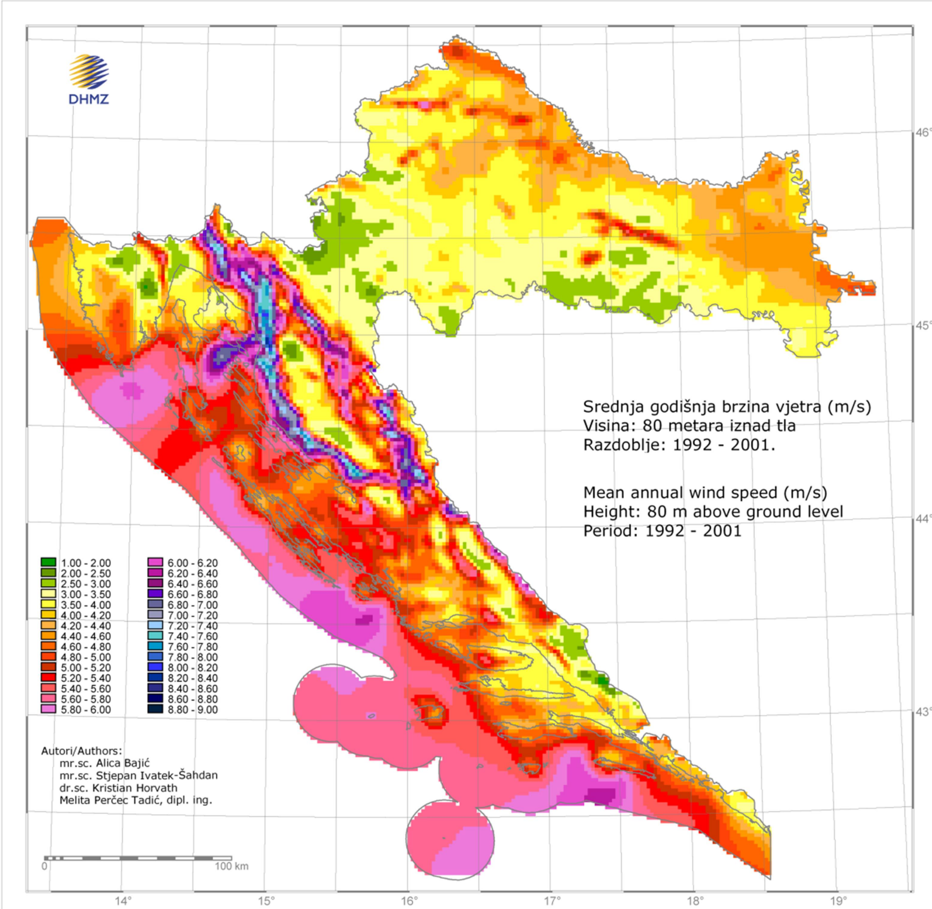


**Fig. 11**: Mean annual wind velocity at 80 m height
(Source: http://meteo.hr/index_en.php)

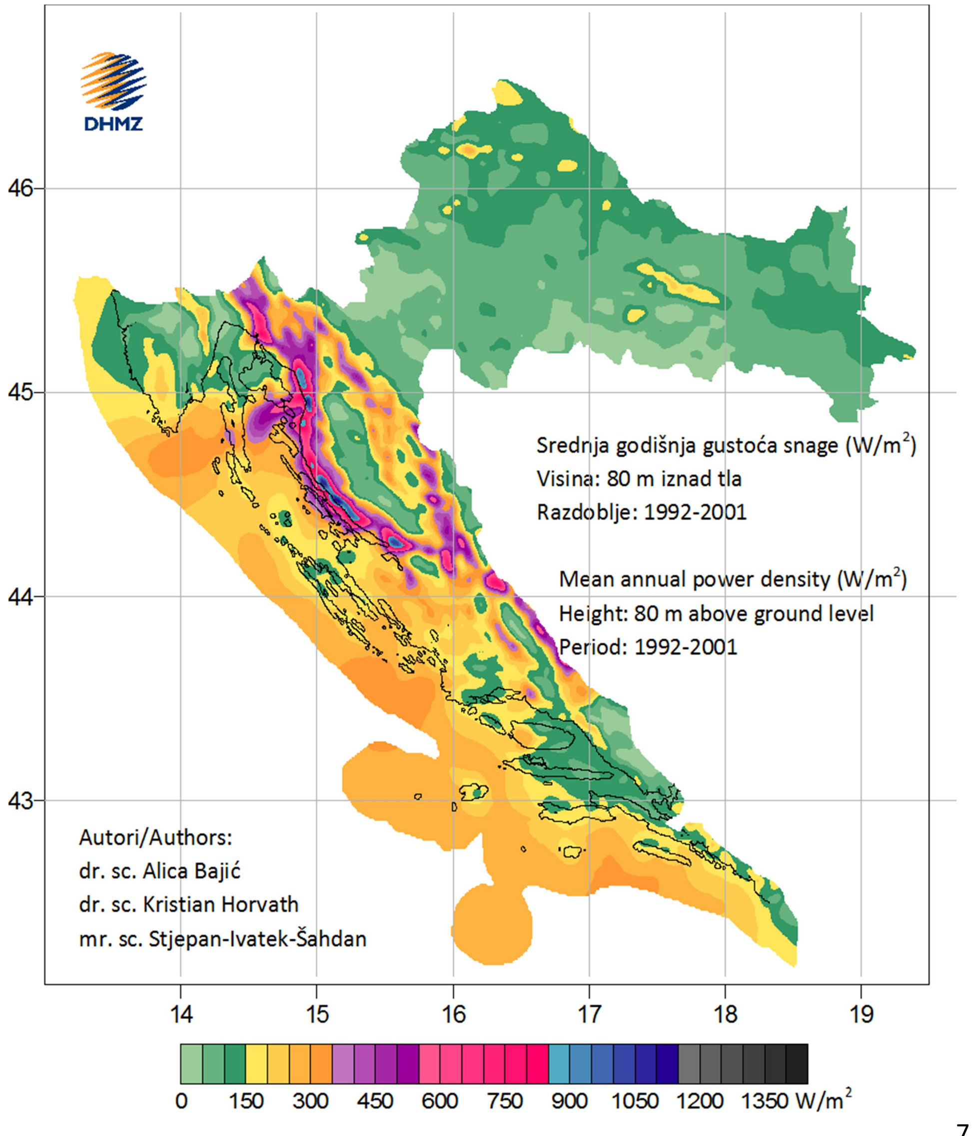


**Fig. 12**: Mean annual power density at 80 m height
(Source: http://meteo.hr/index_en.php)

As is already mentioned in Section 3.1, the sea bottom profile is among the key parameters when assessing the favourable sites for potential OWF development. In **Fig. 13**, the bathymetry of the Adriatic Sea is presented. Shallow and intermediate water depths (-100–0 m) are depicted in the northern part of the Adriatic Sea, whereas in the southern part the water depth reaches values above 1200 m.

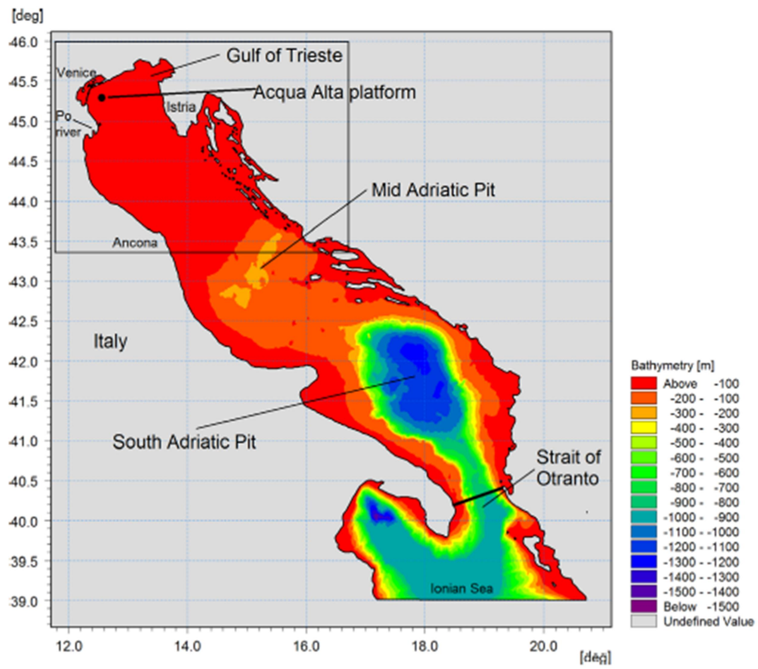


**Fig. 13**: Adriatic Sea bathymetry
(Source: Bolaños et al., 2014).

In **Fig. 14**, a more detailed representation of the water depths in the Adriatic Sea that are taken into account by the offshore wind industry in terms of the current technology (i.e. -200–0 m) is given. Offshore wind turbines with fixed foundation seem to be appropriate for the northern Adriatic Sea (e.g. offshore areas of Istria) while offshore areas of Croatia have water depths between 40 and 100 m, which are suitable mainly for floating wind turbines.

In 2004 the Croatian Government with the “Decision on arrangement and protection of protected sea coastal region” prohibited the construction of onshore wind turbines on Croatian islands, as well as on the mainland in the region within 1000 m from the Adriatic coasts. This is yet another reason for exploitation of offshore wind power in the Croatian part of the Adriatic Sea. Theoretical offshore wind potential within Croatian territorial waters is estimated to be about 150 TWh of electricity (Hadžić et al., 2014).

In the study of Hadžić et al. (2014) three potential geographical locations in the Croatian part of the Adriatic Sea were identified with respect to the following key parameters for offshore renewable energy production:

- wind properties;
- water depth;
- existing navigation routes, and ;
- vicinity of the coastal electrical power network.

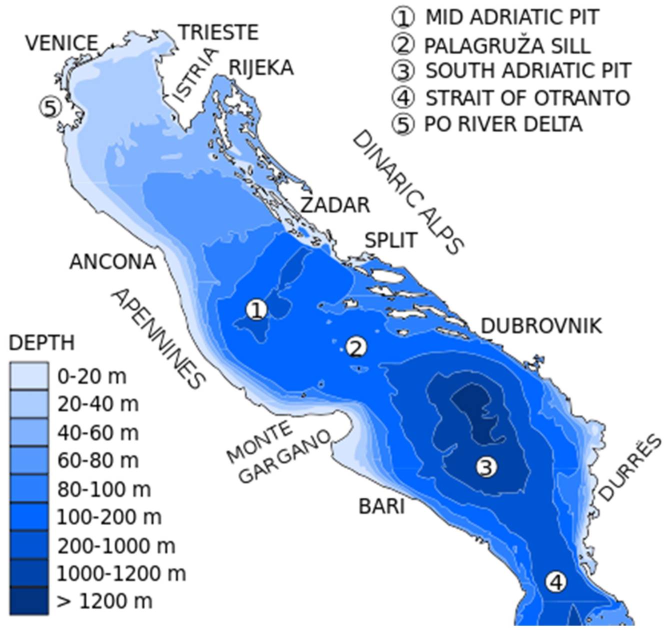


**Fig. 14**: Detail Adriatic Sea bathymetry
(Source: http://www.wikiwand.com/sh/Jadransko_more)

These three potential sites are located offshore:

- the city of Pula and the Lošinj Isl., with maximum water depth at 60 m;
- the city of Šibenik, with maximum water depth at 90 m, and;
- the Mljet Isl., with maximum water depth at 150 m.

**Fig. 15** illustrates the potential offshore wind power plant location at the open sea area close to the city Pula and the Lošinj Isl.

Regional studies as regards offshore wind power potential in Croatia are presented in the following studies:

- Liščić et al. (2014), where two offshore locations of the Croatian coasts were selected for deploying a fixed offshore wind power plant based on wind speed, water depth and ship routes.
- Hadžić et al. (2014), where possible environmental and economic impacts are analysed under the scenario of OWF development in the Croatian part of the Adriatic Sea.

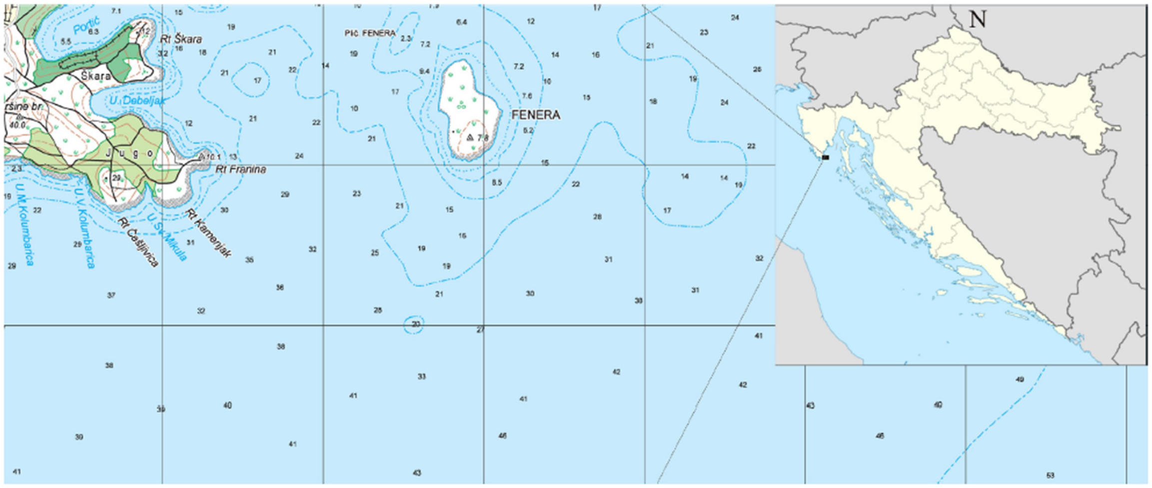


**Fig. 15**: Potential offshore wind power plant location
(Source: Hadžić et al., 2014)

### 4.1.3 France

In the framework of the national energy transition policy, France has designed an ambitious program of diversification of its modes of energy production and the development of renewable energies. The program envisages, in particular, that the share of consumption provided by renewable energies will be increased of 23% by 2020 and 32% by 2030.

In order to obtain a homogeneous description of the wind resources of all metropolitan coasts, METEO FRANCE is operating AROME since 2008. AROME is a meteorological model that simulates the atmosphere in three dimensions, and ensures a three-dimensional physical coherence of the wind. The use of this model has been preferred to measurement campaigns, which are local and limited in time. This model simulates the 10-minute average wind speed at 100 m asl, making feasible the evaluation of offshore wind power capacity for a given area. Furthermore, METEO FRANCE has constituted an offshore wind atlas with the following features:

- wind speed data at 100 m;
- over 10 years of data (2004–2013);
- horizontal resolution of 2.5 km;
- information about the wind force, and;
- information about the wind direction.

As shown in the following map (**Fig. 16**), the spatial distribution of mean wind speed at 100 m height asl off the French coasts are presented. As regards the Mediterranean French coasts, wind speed is accelerated by the local strong wind Mistral resulting in high values at the offshore part (above 9.5 m/s).

Apart from the offshore wind resource potential, other factors have to be taken into account related to maritime spatial planning and the coexistence of different marine/maritime activities. In this context, the Minister of Ecology, Sustainable Development and Energy requested the Regional Prefect to define the most suitable areas for hosting floating installations in the MS, while Provence-Alpes-Côte d'Azur and the Maritime Prefect of the Mediterranean compiled a document in close consultation with the entire maritime community for OWF planning by taking into account technical, economic, social and environmental criteria. Specifically, the following detailed spatial information is included: the most favourable areas for OWF development, no-go areas (due to other marine uses), bird protection zones, electrical grid infrastructure, radar coordination zones (e.g. air defence, civil aviation, S-band weather radars, etc.), limit zones of 10 km, 7 mi, 12 mi and 20 mi, isobaths of 50 m and 100 m, potential zones for aggregate extraction, etc. Let us note that the above information should be necessarily included in detailed and site-specific analyses; see also Soukissian et al. (2015).

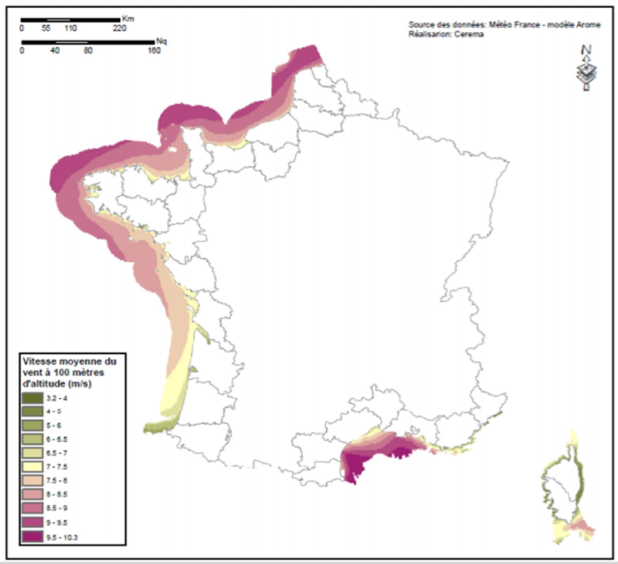


**Fig. 16**: Offshore wind production capacities
(Source: METEO FRANCE)

This planning document allowed the setting up of a Call for Expressions of Interest for the establishment of pilot farms for floating wind turbines in the MS. To prepare it, the coordinating prefects of the façade proposed a delimitation of "less constraints zones". This delimitation, presented in a schematic map below, see **Fig. 17**, is the result of a regional consultation process with the representatives of professional fishermen, maritime transport and air navigation, boating and recreational fishing, environmental associations and managers of marine protected areas, as well as the Ministry of Defence.

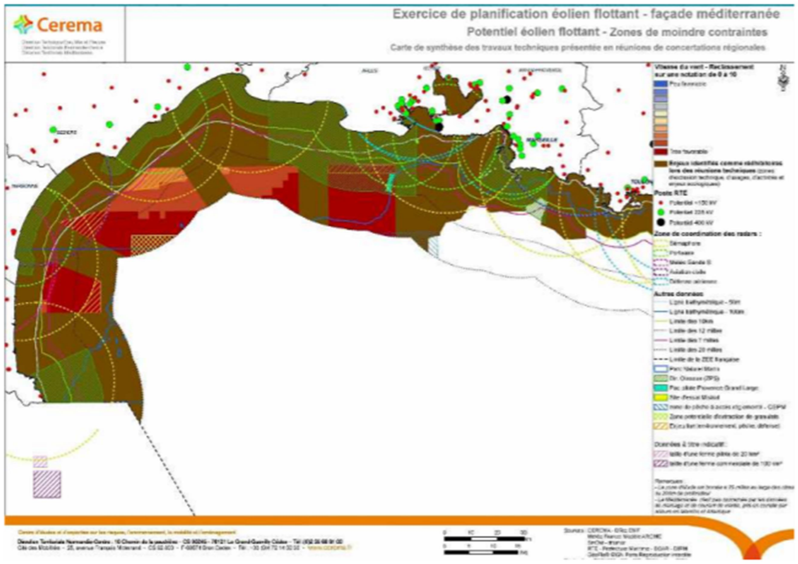


**Fig. 17**: Potential for Floating Offshore wind in Mediterranean
(Source: CEREMA)

The call for the implementation of OWFs was launched in 2015 (M€ 150) with the following specifications:

- 3 to 6 offshore wind turbines per farm (5MW minimum);
- connection to the electricity grid;
- demonstration for 2 years and, in case of success after the pilot period, 15–20 years of offshore wind exploitation, and;
- environmental monitoring during the construction phase as well as 5 years during the operation phase.

The three pilot projects selected with the ambitious objective to be fully operational in 2020 are the following:

- **EOLMED project** in Gruissan led by QUADRAN (partners: Ideol, Bouygues TP, Senvion) with four wind turbines of 6,15 MW;
- **EFGL project "Les Eoliennes Flottantes du Golfe du Lion"** in Leucate area led by Engie (Partners: Caisse des Dépôts, Principle Power, Eiffage and General Electric) with four wind turbines of 6MW;
- **PGL project "Provence Grand Large"** in Faraman area led by EDF EN (partners: Siemens, SBM, IFP EN).

In **Fig. 18**, the site locations of the selected wind farms are depicted in green polygons.

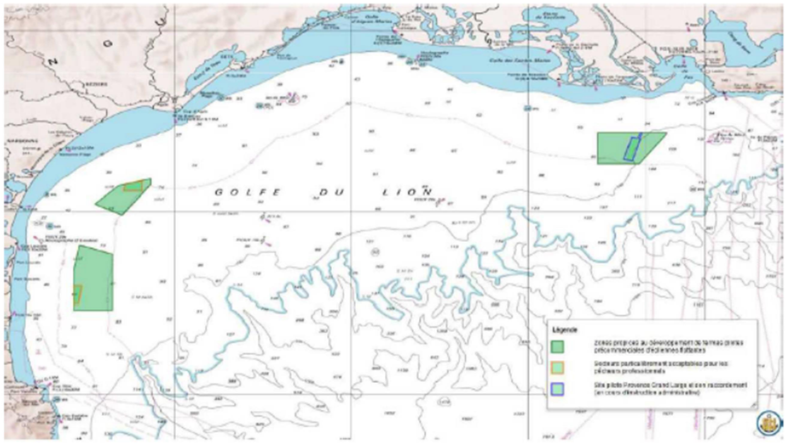


**Fig. 18**: Location of the three French pilot offshore wind farms

### 4.1.4 Italy

As regards the offshore wind energy potential in the Italian Seas, several studies have been performed at a national or regional level. In the following list, some representative analyses are provided:

- Botta et al. (2009), where among others offshore wind energy potential was evaluated taking into consideration water depth and existing and forthcoming technologies;
- Casale et al. (2010), where local offshore wind resource was assessed from *in situ* observations in order to reduce uncertainties and improve the evaluation of the offshore wind potential provided by the Italian wind atlas;
- Foti et al. (2010), where a feasibility study was conducted for the development of an OWF in the gulf of Gela in terms of environmental loads (wind, wave, water level, current) on the foundation of a gravity-based offshore wind turbine;
- Schweizer et al. (2016), where another feasibility study was made off the coast of Rimini (northern Adriatic Sea); except for the estimation of offshore wind potential, additional characteristics such as geological and environmental were also included in the analysis. The authors strongly suggest that this site is favourable for the development of a large OWF;
- Soukissian et al. (2017), where an analytic feasibility study as regards OWF development in the Gargano Sud (Italy) was presented.

### 4.1.5 Spain

For the calculation of the marine wind potential in Spain, reference is made to the final zoning of the "Environmental strategic study of the Spanish coast", approved in April 2009 by the Ministries of Environment and Rural and Marine Affairs, and Industry, Tourism and Trade ([3]).

This zoning was carried out according to the affection degree of potential OWFs, over 50 MW, in each area of the coast, considering socio-economic and environmental concerns. On a general planning scale, the following categories were suggested; see also **Fig. 19**:

- "exclusion zones" (red colour), in which there was an incompatibility between the existence of OWFs (over 50 MW) and already established uses or activities;

([3]) Análisis del recurso. Atlas eólico de España. Estudio técnico (PER 2011-2020).

- "suitable zones with conditions" (yellow colour), where the development of OWFs was conditioned, in the absence of more detailed information, and;
- "suitable zones" (green colour), where no incompatibility was detected, in terms of strategic planning.

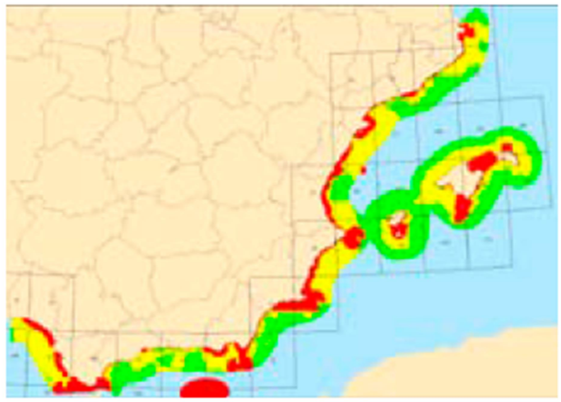

**Fig. 19**: Environmental strategic study of the Spanish coast zones. Mediterranean coast

It was also observed that 75% of the Spanish coasts would be available, *a priori*, for the implementation of OWFs as a result of the zonification of the "Strategic Environmental Survey of the coast", requiring detailed studies to determine the final environmental viability. In **Table 1**, the area for the above-mentioned categories are provided along with the corresponding percentages. Potential areas that are favourable for OWF development under conditions have the highest percentage (39%) while the excluded zones have the lowest one (24.3%).

| | EEAL zonification | |
|---|---|---|
| | Useful area ($km^2$) | Area (%) |
| Apt | 84,666 | 36.8 |
| Conditioned | 89,759 | 39.0 |
| Excluded | 55,889 | 24.3 |
| Total | 230,313 | 100 |

**Table 1**: Type of area regarding the EEAL zonification type

See also the recent study of Rodríguez-Rodríguez et al. (2016). In the following table (**Table 2**), the distribution of wind speed ranges, at 80 m asl, of the sea surface of Spain regarding the "apt" and "suitable with conditions" zones (without considering the so-called "exclusion") is shown. 41.02% of the considered areas are characterized by wind speeds greater than 7.5 m/s; wind speeds higher than 9.5 m/s hold 5.13%.

A mean annual wind speed of 7.5 m/s at 80 m asl could be used as a reference for the minimum marine wind resource required at an offshore site. In this sense, only 41% of the sea surface in Spain was not excluded in the "Strategic Environmental Survey of the coast" and could have enough wind conditions to initially consider the implementation of offshore projects, including deep-sea areas, always considering the uncertainty associated with the methodology used in the evaluation of the wind resource and the technological evolution of the sector.

| Wind speed (m/s) | Area ($km^2$) | Area (%) |
|---|---|---|
| <4 | 369 | 0.21 |
| 4-4.5 | 319 | 0.18 |
| 4.5-5 | 577 | 0.33 |
| 5-5.5 | 3,319 | 1.9 |
| 5.5-6 | 12,707 | 7.29 |
| 6-6.5 | 29,889 | 17.14 |
| 6.5-7 | 26,351 | 15.11 |
| 7-7.5 | 29,344 | 16.82 |
| 7.5-8 | 28,169 | 16.15 |
| 8-8.5 | 13,652 | 7.83 |
| 8.5-9 | 10,517 | 6.03 |
| 9-9.5 | 10,264 | 5.88 |
| 9.5-10 | 6,617 | 3.79 |
| >10 | 2,331 | 1.34 |
| Total | 174,425 | 100 |

**Table 2**: Breakdown of available surface for potential OWF development based on wind speed ranges

The first prototype of an offshore wind turbine at deep waters (at 220 m, 2.3 MW) was launched in Norway in October 2009. All commercial OWFs in the world, and of offshore wind projects in Spain, are referred to bathymetric depths of less than 50 m. Therefore, with the current status of offshore wind technology, and considering the 2020 horizon, all the commercial OWFs (not including R&D in deep waters, for experimental purposes) considered to be placed in Spain should be located in depths less than 50 m.

Consequently, in order to calculate the offshore wind potential in Spain, OWFs could only be installed in places with a depth equal to or less than 50 m. By the implementation of this technical restriction, the offshore areas of the Spanish Mediterranean coasts with suitable depths are diminished as regards their surface considerably. In **Fig. 20**, this decrease is schematically depicted.

It was considered that marine sites with a mean annual wind speed of less than 7.5 m/s at 80 m - estimated hub height for a marine wind turbine - will render a marine wind project in that area technically and economically non-viable. It was estimated that this average speed could be of the order of 2,650 equivalent net operating hours, considering the power curve described in (PER 2011-2020) and overall losses between 15% and 20%.

**Fig. 20**: EEAL zones filtered with bathymetry. Mediterranean Coast

Applying the results of the present study of the wind resource as a reference for the filtering of wind speeds in excess of 7.5 m/s to 80 m in height, the available areas of the Spanish coast that would have a sufficient wind resource are shown in **Fig. 21**. In order to include also the environmental criteria and the maximum permissible water depth of the previous subsections, the suitable areas would be further reduced.

**Fig. 21**: EEAL zones filtered with bathymetry and offshore wind resource. Mediterranean coast.

In summary, the following conclusions were obtained from the calculation of that marine analysis:

- After the application of technical and economic data filters associated with bathymetry (above -50 m) and the necessary wind resource (v ≥ 7.5 m/s, 80 m asl), it was concluded that the Spanish coastline would have about 3,500 $km^2$ of useful surface area for offshore wind development.
- Of this useful surface, 60% would be excluded for the implementation of OWFs (power of more than 50 MW) for the environmental considerations of the "Coastal Environmental Strategic Survey".

These results greatly limited the development of offshore wind on the Spanish coast, despite the seemingly extensive areas available in the maritime-terrestrial public domain: about 23 million ha in the 24-mile band, with 4,830 km of coast in the Peninsula and another 3,049 km of coast in the insular and extra-peninsular systems (according to IGN data in its "National Atlas of Spain").

| | EEAL zonification of offshore wind farms | | Bathymetry filter (cotas more than -50m | | Offshore resource filtering (v>7.5 m/s, 80 m high) | |
|---|---|---|---|---|---|---|
| | Coast area ($km^2$) | Area (%) | Rest area ($km^2$) | Area (%) | Rest area ($km^2$) | Area (%) |
| Apt zones | 84,666 | 36.8 | 512 | 2.7 | 31 | 0.9 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Apt zones with conditioning | 89,759 | 39 | 6,110 | 32.5 | 1,381 | 39.1 |
| Exclusion zones | 55,889 | 24.3 | 12,159 | 64.7 | 2,116 | 60 |
| Total Spanish coast | 230,313 | | | | | |
| Apt area for filtered | 174,425 | | 6,623 | | 1,412 | |
| % apt from the total area | 75.73 | | 2.88 | | 0.61 | |

**Table 3**: Available area in the Spanish Coast, regarding EEAL zonification

Ratio of offshore wind per unit area

A last but rather essential hypothesis of great relevance in the calculation of the available wind power potential in terms of power is the number of offshore wind turbines and their unit power that can be reasonably located in each unit of surface with sufficient potential.

In the case of the onshore wind potential, this calculation was highly sensitive due to the evolution of the technological level of wind turbines; so it was not a stable value over time. However, a good estimate could be obtained from the average marine utilization ratio of around 6 MW/km$^2$, associated to the thirty real wind projects in Spain at the end of 2009, submitted to the Ministry of Industry, Tourism and Trade for a Joint global power above 7,500 MW (several in concurrence, and some located in exclusion zones).

Applying this average occupation rate, the marine wind potential in the Spanish coasts, in the areas classified as "apt" and "suitable with conditions" by the Environmental strategic study of the coast (for the implementation of offshore wind farms, with an output of more than 50 MW), in the above-mentioned bathymetric conditions and the availability of enough wind resources, would be about 8,500 MW (and about 5,000 MW for sites with average wind speeds of over 8 m/s, 80 m asl).

It is important to emphasize that the effective surface area due to environmental considerations will be even lower because, as already mentioned, the definitive environmental aptitude for the introduction of offshore wind technology in areas classified as "apt" and "suitable with conditions" will be determined for each specific project, after the necessary detailed studies.

As regards local/regional studies, EWEA set the overall offshore wind power installed in Spain about 5 MW (Colmenar et al., 2016), and corresponded to Gamesa wind turbine (G128) 5 MW, placed in Arinaga (Las Palmas de Gran Canaria). Nonetheless, the offshore wind energy in Spain is in a standstill state and currently there are no projects planned for the implementation of offshore windfarms (Colmenar et al., 2016).

Several projects were planned until 2008 for the implementation of OWFs in the Spanish coasts. The Acciona project for the installation of 1000 MW in the Sea of Trafalgar (Colmenar et al., 2016), the 300 MW of the company Capital Energy in Tarragona-Castellón waters were between the most prominent projects and Iberdrola Renewables offshore wind area requested to develop research activities for several projects such as Costa de la Luz (Huelva), Punta del Gato (Huelva), Punta de las Salinas (Castellón), Costa de Azahar (Castellón), Costa de la Luz (Cádiz) and Banco de Trafalgar (Cádiz). Each of the latter projects will have an estimated capacity around 500 MW (Colmenar et al., 2016). Nonetheless, all projects are not currently being developed without any characterization of offshore wind zones (Colmenar et al., 2016).

The Royal Decree-Law 9/2013, of July 12th stated imperative measures to guarantee the financial stability of the electrical system taken. The pre-allocation procedures were temporarily stopped and economic incentives for new installations of cogeneration, renewable energy and waste were removed (Colmenar et al., 2016). Therefore, the efforts for the development of the offshore wind technology have been closed.

This situation has not changed after the approval of Royal Decree 413/2014, of June 6th, where the activity of electricity production from renewable energy sources, cogeneration and waste was controlled, switching the incentive system to a specific remuneration regime for these types of technologies that provide investment incentives.

Besides, the removal of feed-in tariffs for renewable energy and the lack of public funds from the economic crisis have also led to the freezing of the ZEFIR project (Colmenar et al., 2016). It included the development of a test platform for deep water wind turbines, whose implementation was planned on the coast of Tarragona (Spain) and aimed to be used as a pilot site to test the new technology needed (Colmenar et al., 2016).

However, the sector has a major capacity in R&D, enhancing the continuity of several R&D&I projects (Colmenar et al., 2016). Specifically, the Spanish project FloCan5 was going to receive an EU grant of 34 million euros. It is a wind platform that will be located between 1.5 and 3.7 km from the southeast coast of Gran Canaria, which will be based on five wind turbines of 5 MW, with an overall capacity of 25 MW.

Another Spanish offshore wind platform, with two turbines of 5 MW and two more of 8 MW (Colmenar et al., 2016) will be located in the Bay of Biscay, on the coast of Armintza, and will receive more than 33 million euros.

In addition, the Basque Government and Gamesa followed a strategic infrastructure project in deep waters for the development of floating offshore wind platforms made of steel and concrete, as well as the construction, operation, maintenance phases, and electrical evacuation infrastructures (Colmenar et al., 2016).

## *4.2 Current estimates of current/tidal energy at local/regional scales of the Mediterranean basin*

So far, little attention has been given to the weak tides and currents observed in the Mediterranean straits. However, tidal energy generation at lower energy sites may be of lower risk, as they tend to present lower variability in the annual practical power of tidal currents than higher energy site, as was suggested by Robins et al. (2015). Some recent studies are presented in this section.

### 4.2.1 Greece

A recent study taking into account the current/tidal energy in the area of Halkida in Greece, focused on the Euripus Strait, was performed in Kontoyiannis et al. (2015). See also Ktena et al. (2015). The results obtained from this work indicated that the 2-month average annual power density values of the cross section at the Old Bridge vary spatially within the cross section from

~1.16 kW/m$^2$, in the upper four meters of the section-edge near Evia, to ~0.65 kW/m$^2$, in the deeper four meters of the section, while the section-mean instantaneous APD values on full-moon and new-moon days can be as high as ~7 kW/m$^2$, assuming no loss due to hydro-turbine efficiency. For a hydro-turbine which functions only for flow velocity greater than~50 cm/s and with a nearly constant efficiency of ~40–45% for all velocity values higher than 50 cm/s, the corresponding 2-month average power density values at the Old Bridge vary from 0.50 kW/m$^2$, in the upper 4 m, to 0.26 kW/m$^2$ in the deeper four meters of the section. Based on the use of turbines that are suitable for the space limitations imposed by the examined area, the potential amount of tidal-stream energy in the strait is insufficient for wide-scale applications.

### 4.2.2 Croatia

In **Fig. 22**, the Adriatic Sea current flows are presented. As noticed the prevailing current flow is counter-clockwise from the Strait of Otranto, along the eastern Adriatic coast and back to the strait along the western Adriatic coast.

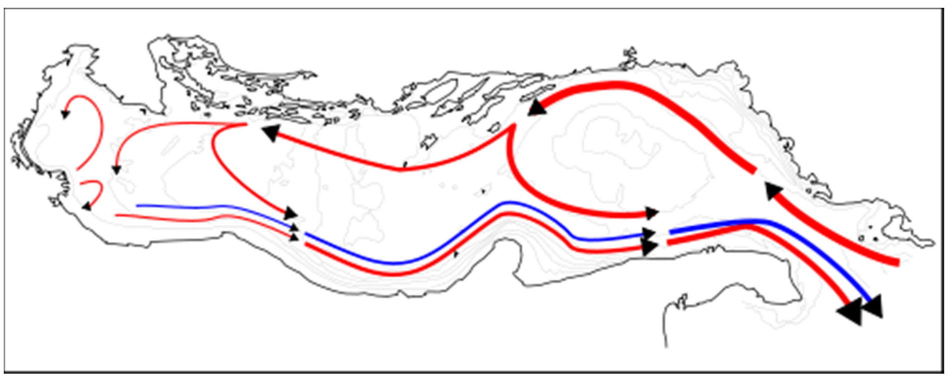

**Fig. 22**: Schematic layout of Adriatic Sea currents: red - surface currents; blue - benthic currents (Source: https://en.wikipedia.org/wiki/Adriatic_Sea)

In the study of Hadžić et al. (2014), four potential geographical locations in the Croatian part of the Adriatic Sea were identified regarding the potential for development of offshore tidal power plants, including: (a) off the Dugi Otok Isl.; (b) off the Mljet and Lastovo Isl.; (c) off the Vis Isl., and; (d) the North Adriatic Sea.

The study states that the mean sea current speed, ranging from 0.20 to 0.24 m/s, at these locations is quite low and consequently low level of energy is produced. Therefore, in order to identify other potential locations with favourable sea current conditions further measurements and research is required. **Fig. 23** illustrates the potential offshore tidal current power plant location corresponding at the open sea of the city Pula.

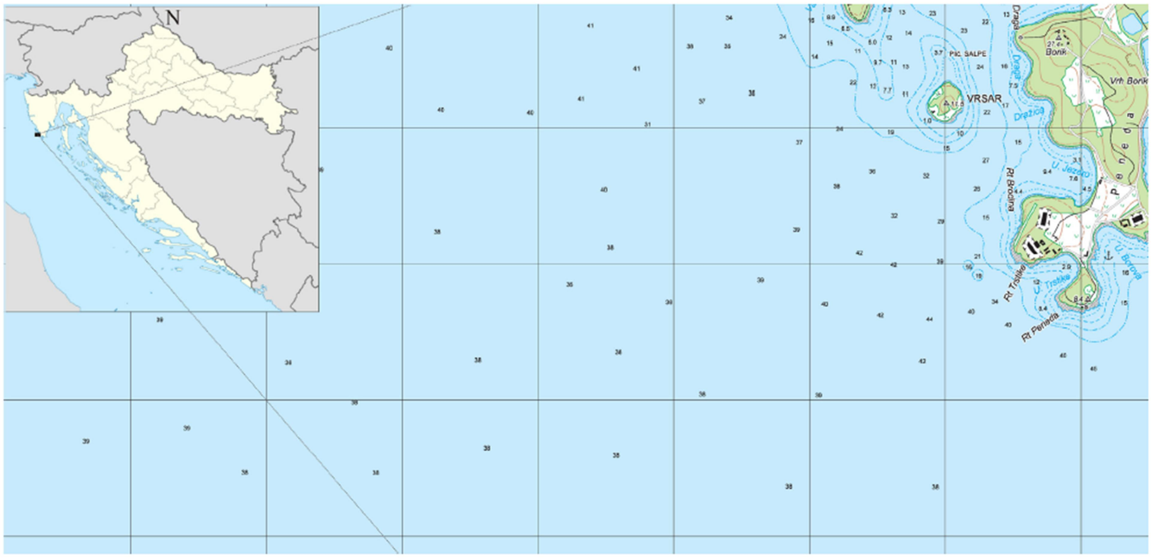


**Fig. 23**: Potential tidal current power plant location
(Source: Hadžić et al., 2014)

Regarding the regional scale, in Bolaños et al. (2014) the current dynamics of the northern Adriatic Sea were analysed with the use of MIKE3/21 modelling system along with measurements (wind, wave, sea level, current). After performing a 1-year long simulation, the behavior of currents and their correlation with wind events and tides have been analyzed.

Tidal movements in the Adriatic are slight, although larger amplitudes are known to occur occasionally. However the tidal range of at least 7 m, defined by the Ocean Energy Council as a good range for exploiting tidal energy (http://www.oceanenergycouncil.com/ocean-energy/tidal-energy/), is not observed in the Adriatic Sea.

### 4.2.3 Italy

The narrows through the Strait of Messina are characterized by high-energy tidal currents with maximum velocities at spring peak tides ranging from 1.8 m/s to more than 3 m/s, proving the suitability of the site for tidal energy harnessing, El-Geziry et al. (2009). See also Coiro et al. (2013).

### 4.2.4 Spain

An assessment of the tidal current energy potential was made by González-Caballín et al. (2016) for the case of the estuary of Avilés port. Avilés port is placed in a river estuary in the north coast of Spain and flows into the Cantabrian Sea, southernmost part of the Bay of Biscay. It is a channel of 5000 m length with an average width of 160 m and a nearly steady depth of 11.5 m.

González-Caballín et al. (2016) reported a high resolution two-dimensional (2D) equivalent model of the port that consisted of a longitudinal section (including depth and length) justified by the large width of the channel in relation to its depth. Moreover, a simulation methodology using Computational Fluid Dynamics (CFD) was used to obtain the velocity field in different parts. Using the latter information, an overall assessment of its tidal current energy potential was achieved.

## 4.3 *Current estimates of wave energy at local/regional scales of the Mediterranean basin*

### 4.3.1 Greece

The spatial distribution of the mean annual values of both significant wave height and wave direction are presented in **Fig. 24** ([4]). The length of the arrow as regards wave direction is equal at every grid point. In brief, in the northern Aegean Sea, the mean wave directions are eastern and north-eastern, in the central part they turn to northern and for the rest part of the Aegean Sea they are north-western. In the Ionian Sea, western and north-western wave directions are prevailing in the central and southern part, while mainly south-western wave directions are dominant in the northern part.

In **Fig. 25**, the spatial distribution of mean annual wave energy flux for the period 1979–2013. In the offshore area western of Crete Isl. the highest value of mean annual wave energy flux is depicted close to 5.77 kW/m. Moreover, southern of Crete Isl. and in the central part of the Aegean Sea (between Tinos and Chios Isl.) rather high values of the same parameter are observed (of the order of 5.5 and 5 kW/m, respectively).

The corresponding pattern of mean wave energy flux for the four wave seasons, i.e. winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November), is described as follows (figures are not presented here):

- The mean wave energy flux in winter presents the highest value of wave energy flux for the entire Greek domain regarding the examined period. The area with the overall highest value is located at the western part of Crete Isl. with value up to 12.45 kW/m, while both the western and southern part of the same island present systematically values higher than 8.32 kW/m.
- Spring is the season with the second highest values of wave energy flux and with similar spatial distribution with the one presented for winter. Again, in the western part of Crete Isl. the highest value of mean annual wave energy flux is depicted (5.27 kW/m).
- During autumn the corresponding wave energy flux presents lower peak values compared with spring in the central Aegean Sea, with values up to 4.97 kW/m (eastern of Andros Isl.). Western of Crete Isl. wave energy flux is equally high (4.59 kW/m).
- Finally, summer is the season with the lowest values of wave energy flux. The highest value is observed southeast of Crete Isl. (3.46 kW/m) while in southern Ionian Sea and western of Crete Isl. there is an overall reduction in the wave energy flux (<2.1 kW/m).

Other more local assessments of the wave resource have been presented, among others, in Soukissian et al. (2012) for particular offshore locations of the Greek Seas. The entire Aegean Sea (along with the eastern Mediterranean) has been assessed as regards wave energy potential by Ayat (2013). In this study, a spectral wave model was implemented between 1994 and 2009 and some Greek Isl. with wave potential over 4 kW/m were identified from the obtained results. In Jadidoleslam et al. (2016), a wave power atlas is presented for the Aegean Sea from 1999 to 2013 using the spectral wave model MIKE21 SW, which was calibrated from *in situ* measurements obtained from nine buoys, verifying its high accuracy. In Emmanouil et al. (2016), wave energy assessment in the Greek seas was conducted based on a 10-year database of wind and wave data obtained by numerical models with horizontal resolution 0.05° x 0.05°. The results showed that western and southern part of Greek seas have the highest wave energy potential.

([4]) The results presented for Greece have been obtained from the AVRA project.

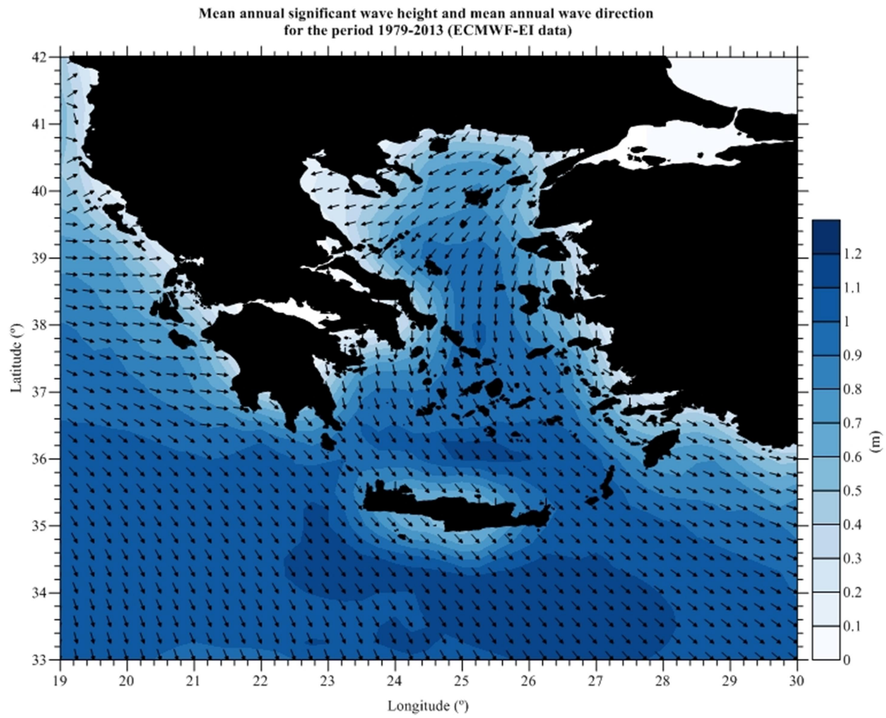


**Fig. 24**: Spatial distribution of mean annual significant wave height and mean annual wave direction in the Aegean and Ionian Seas for the period 1979–2013
(Source: AVRA project)

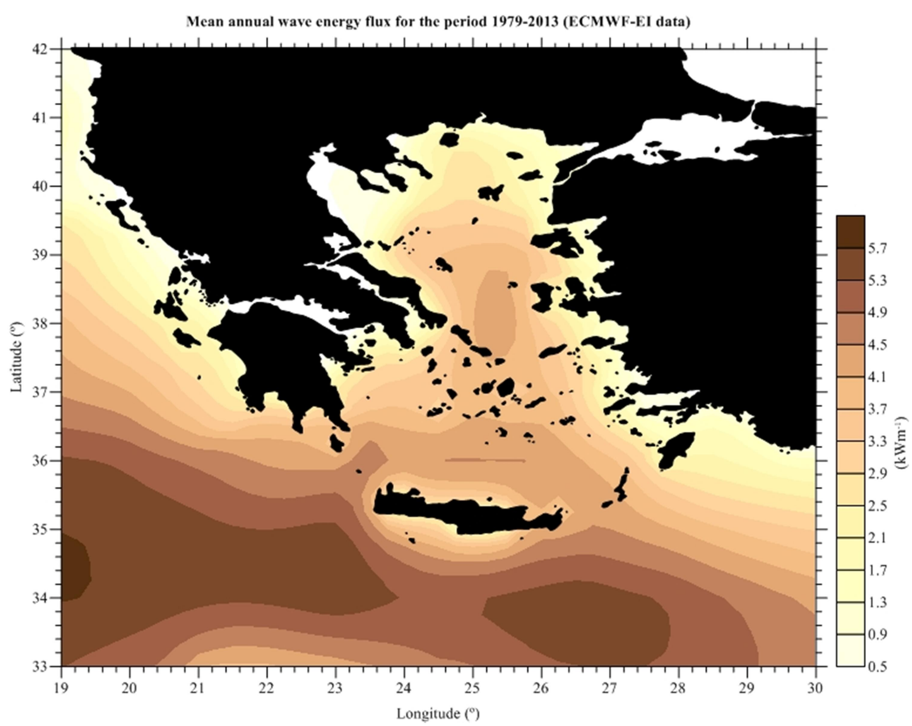


**Fig. 25**: Spatial distribution of mean annual wave energy flux in the Aegean and Ionian Seas for the period 1979–2013
(Source: AVRA project)

### 4.3.2 Croatia

Adriatic Sea is a semi-closed sea with low water depths, especially in the north. Therefore, surface waves in general depend on wind speed, wind direction and duration of the prevailing winds. It has been reported that during winter 90% of the wave heights are lower than 2 m (http://skola.gfz.hr/d6_9.htm). These values are given for the open sea, while in coastal areas significantly smaller waves are present. Therefore, the potential of using wave for power production is less efficient.

### 4.3.3 Italy

The western coast of Sardinia is characterized by the highest wave energy in the whole Mediterranean basin, as already mentioned in Section 3.3.2. Another region of interest indicated in Liberti et al. (2013), is represented by the north-western edge of Sicily. For these two regions a detailed overview of the average wave power per unit crest has been computed over the entire simulated period along a line at a distance of about 12 Km off the coast for the two regions; see **Fig. 26** and **Fig. 27**. The analysis has shown the considerable variability of the average power flux at spatial scales of the order of the tens of kilometres. The maximum productivity of about 12 kW/m is found in two areas located in the northern and southern sections of the western coast of Sardinia, respectively. In Sicily, the highest values of about 7.5 kW/m are reached just in the western extreme of the island, while the rest of the coast is far less energetic.

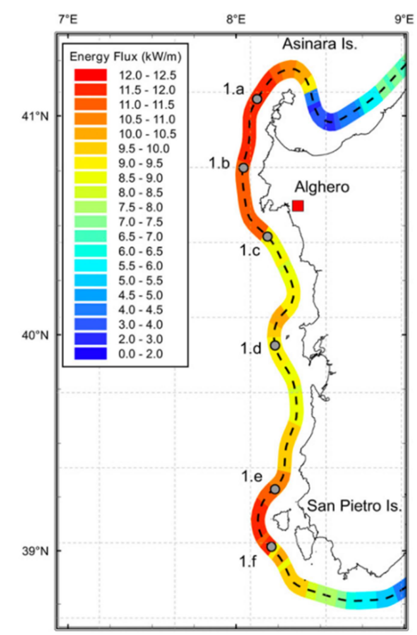


**Fig. 26**: Distribution of average wave power flux per unit crest on western Sardinia coastline. Values are calculated on a line located 12 km off the coast
(Source: Liberti et al., 2013)

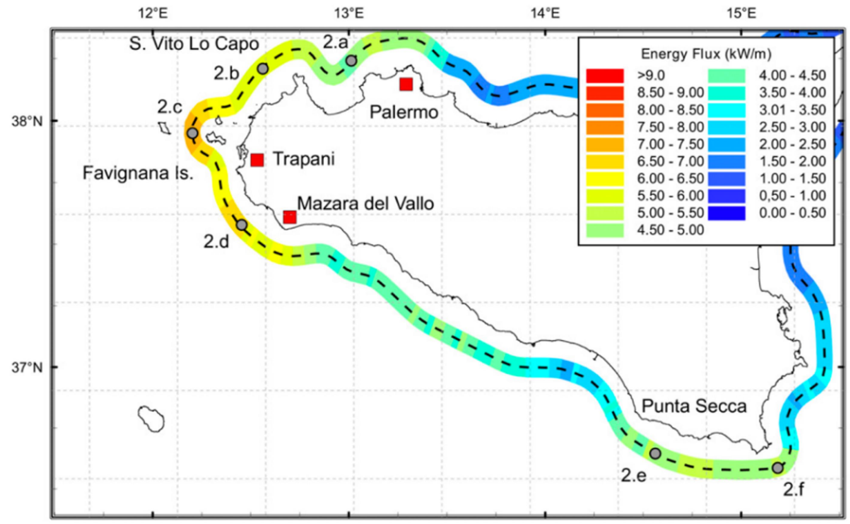


**Fig. 27**: Distribution of average wave power flux per unit crest on the north-western and southern coastline of Sicily. Values are calculated on a line located 12 km off the coast.
(Source: Liberti et al., 2013)

The characterization of the sea states in terms of the energy availability under different conditions of wave height and period is of essential importance in WECs feasibility studies. As an example, in **Fig. 28**, for two points along the Sardinia and Sicily coasts, the scatter plot representing the distribution of yearly average energy in terms of wave energy period and significant wave height is shown, evaluated over the 10 years simulated period. Contribution to the total energy given by individual sea states are lumped together in 0.25 s intervals of wave energy period and 0.25 m intervals of significant wave height. Lines of constant power are drawn as a reference on the scatter plot. Wave power contributions of individual 3-hour sea states obtained from the model output are calculated using Eq. (3).

The distributions in **Fig. 28** show the different ranges of heights and periods in the two locations. In the Sardinia location, the most energetic contributions are found in the range between 6 and 10 s of wave period and in the range between 2 and 6 m of wave height. In the Sicilian site the main contributions to total energy are found in a lower range of periods (between 6 s and 8 s) and of heights (between 1.5 m and 4 m). The wave potential along the north-western coast of Sardinia has been analysed also by Vicinanza et al. (2013), who have identified “hot-spots”, using a high resolution numerical propagation model, where the wave power reaches values close to 11 kW/m.

Another study, conducted by Vannucchi & Cappietti (2016), deals among others with the assessment of wave power at four locations in Italy, namely coasts of Tuscany, Liguria, Sardinia and Sicily. Furthermore, the annual, seasonal and monthly variability of wave power at two water depths (50 m and 15 m) were estimated while hotspots at each location were identified. The obtained results showed that the most energetic area of the examined Italian nearshore locations is in Sardinia (at 20 m water depth) with total mean annual energy close to 100 MWh/m. Furthermore, there is strong variability of the wave energy potential (from point to point) even at the same area; thus, the need for in-depth analysis in the spatial scale was highlighted.

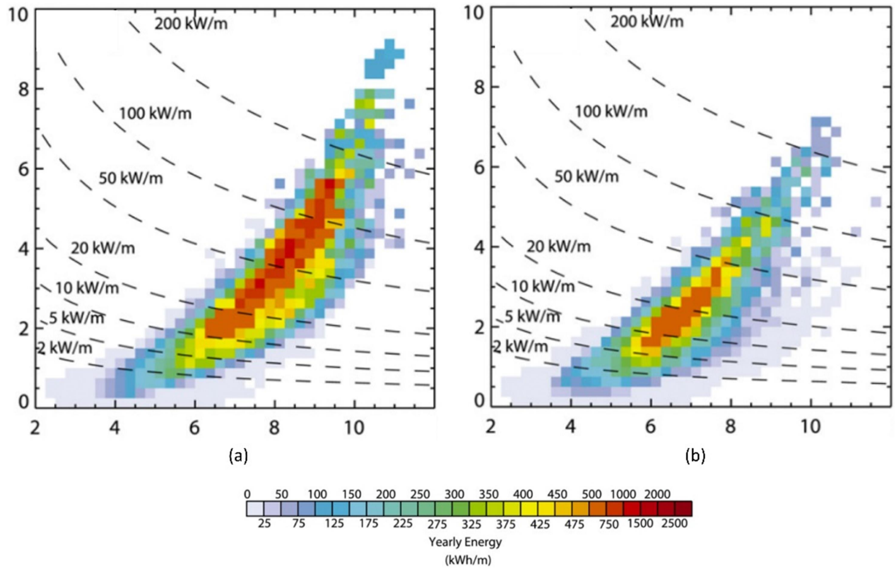


**Fig. 28**: Distribution of yearly energy among energy period (x axis) and significant wave height (y axis) (a) for point 1 in **Fig. 26**, (b) for point 2 in **Fig. 27**
(Source: Liberti et al., 2013)

Wave energy assessment around the Sicily Isl. has been performed by Monteforte et al. (2015) and Iuppa et al. (2015). Both studies reveal hot-spots for a possible development of wave energy farm around the examined island; however, further technical-economic feasibility analyses are necessary. On the other hand, a local wave energy assessment was made by De Mendoza et al. (2016) in the northern Latium coast (Italy) by using a numerical wave model (CMS-Wave). Based on the results of this study, the examined site seems to be optimal for installing wave energy devices combining the energy availability, accessibility easiness and limited environmental impact.

### 4.3.4 Spain

Spain is a country with great potential for wave energy, due to its extensive coastline, mainly on the north coast, bathed by a sea with an abundant resource, stable and predictable, all ideal factors for the generation of wave energy; see e.g. Iglesias et al. (2010) and Iglesias & Carballo (2010).

Currently, Spain is one of the main countries where different technologies are being developed in this field and aims to become a benchmark and world leader of the future. The Galician coast has the highest energy potential values, with an average power between 40–45 kW/m. The Cantabrian Sea is the next coastal zone in terms of resource, about 30 kW/m. The Mediterranean and the Gulf of Cadiz have annual mean values of less than 10 kW/m. Several prototypes of wave energy have already begun to be tested in different areas of the country, with the ultimate goal that in a few years the strength of the waves could become a renewable energy source.

Regional studies focusing on wave energy resource assessment can be found in Sierra et al. (2014) for Menorca Isl., and Ponce de León et al. (2016) for the Balearic Sea.

## 4.4 *Current estimates of ocean thermal conversion and salinity gradients energy at local/regional scales of the Mediterranean basin*

Ocean thermal energy conversion technology in the MS is currently not in the short-term plans for development mainly due to the existing status of the technology (systems of low performance) and the temperature differences of the water column are so low that the minimum exploitable threshold is not feasible; see also Section 3.4.2. Some preliminary results as regards the salinity gradients are presented herewith.

### 4.4.1 Croatia - Italy

In the Adriatic Sea, the salinity is lower compared to the rest sub-basins of the MS because it is influenced by a large river contribution; in this respect, the Adriatic Sea represents a dilution basin. In **Fig. 29**, the spatial distribution of the salinity gradient at the seasonal scale is presented. From top to bottom, the spatial distribution of this parameter is shown for winter, spring, summer and autumn in the Adriatic Sea. At all seasons, it is evident that there is an increase of the salinity gradient from the northern to the southern Adriatic Sea. The most important river flow into the northern Adriatic Sea is the Po River, which, along with other river discharges, reduces the salinity in this region (30–37 psu) mainly during spring (including snowmelt) and autumn. In the Croatian coasts and the Ionian Sea, the corresponding value is around 38–39 psu.

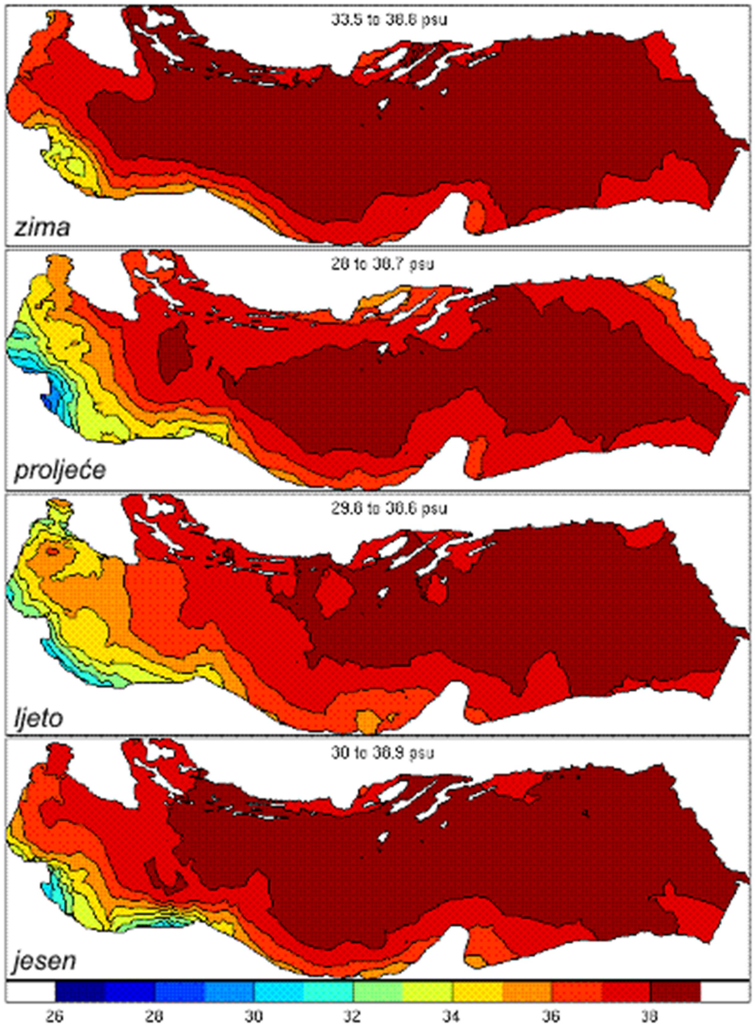


**Fig. 29**: Adriatic Sea salinity gradients in a seasonal scale
(Source: http://skola.gfz.hr/d3_1c.htm)

## 5 Summary and Conclusions

The importance of exploitation of ocean energy resources is due to the rapidly increasing need to replace fossil fuels with sustainable energy. The proven economic viability of offshore wind production in the North Sea along with the maturity of the technology and the wind energy market render offshore wind energy the most promising MRE source for the MS in the near future. Furthermore, offshore wind resource availability seems to be suitable for fostering the development of OWFs in the MS. On the other hand, wave and tidal energy are still not commercially established while the corresponding resource availability that was estimated in the context of numerous studies seems to be rather low, but stable, compared to the North Sea. The concept of harvesting water temperature differences and salinity gradients has both knowledge and technical gaps that should be filled in order to realistically discuss this perspective in the Mediterranean basin.

Summarizing the above-mentioned results of the reviewed marine energy sources for the Mediterranean, the following features are highlighted:

- Offshore wind industry is the most promising sector for development in the MS while the use of floating wind turbines seem to be well-adapted in the geomorphological conditions of the basin. Offshore areas of Greece, Italy, France and Spain have high wind energy resource; however, this asset should be combined with other technical, socio-economic and environmental characteristics in order to provide a viable and sustainable solution.
- The commercial development of the tidal energy sector is not feasible yet in the Mediterranean. Only specific spots may satisfy the current speed limits for the existing technology of tidal turbines; strait of Messina and straits of Dardanelles are characteristic examples. Nevertheless, further studies are essential.
- Due to the low maturity level of wave energy converters technology, at the moment it is not possible to identify a best performing device for the Mediterranean basin. Although the estimated potential of the resource in the Mediterranean Sea is low, the reduced impact of extreme events on devices can make their operational costs affordable. Moreover, hybrid systems, combining exploitation of offshore wind and wave, may provide an alternative solution.
- Applications of ocean thermal energy and osmotic power in the Mediterranean Sea are currently unlikely due to the high installation and operation costs and the maturity of the corresponding technologies.

Overall, experience has shown that improvement of policy frameworks, simplification of licensing procedures, financial stability and effective financing tools are key parameters to facilitate marine energy in the MS. Additional significant drivers towards sustainability in the examined basin is the development and establishment of Marine Spatial Planning and Integrated Coastal Zone Management that will confront possible conflicts among the marine/maritime users, combined also with environmental impact assessment studies.

# 6 Glossary-Abbreviations

| | |
|---|---|
| BWEA | British Wind Energy Association |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| EU | European Union |
| EU-OEA | European Ocean Energy Association. EU-OEA is a network of ocean energy experts (including industry, research institutes, etc.), set up with the EC support, that represents the ocean energy sector of Europe |
| EWEA | European Wind Energy Association. EWEA is a non-profit association comprising of members active in the wind energy sector |
| FiT | Feed-in tariff |
| GWEC | Global Wind Energy Council. GWEC is the international trade association for the wind power industry |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| IRENA | International Renewable Energy Agency |
| MPA | Marine protected area |
| MRE | Marine renewable energy (-ies) |
| MS | Mediterranean Sea |
| NOAA | National Oceanic and Atmospheric Administration |
| O&M | Operation and maintenance |
| OE | Ocean energy |
| ORE | Offshore renewable energy |
| OTEC | Ocean thermal energy conversion |
| OWF | Offshore wind farm |
| RES | Renewable energy sources |
| TEC | Tidal-stream energy converter |
| WEC | Wave energy converter |

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