Feasibility study for wave energy converters in the port of Mola di Bari

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Contents

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EUROPEAN UNION

1 Pilot area

The Apulia Region has 870 km of coastline divided between the Adriatic Sea to the East and the Ionian Sea to the West. It is the Adriatic region in Italy with the most favourable conditions for the deployment of wave energy converters, thanks to deeper seabeds, a steeper seabed morphology, and better wind conditions.

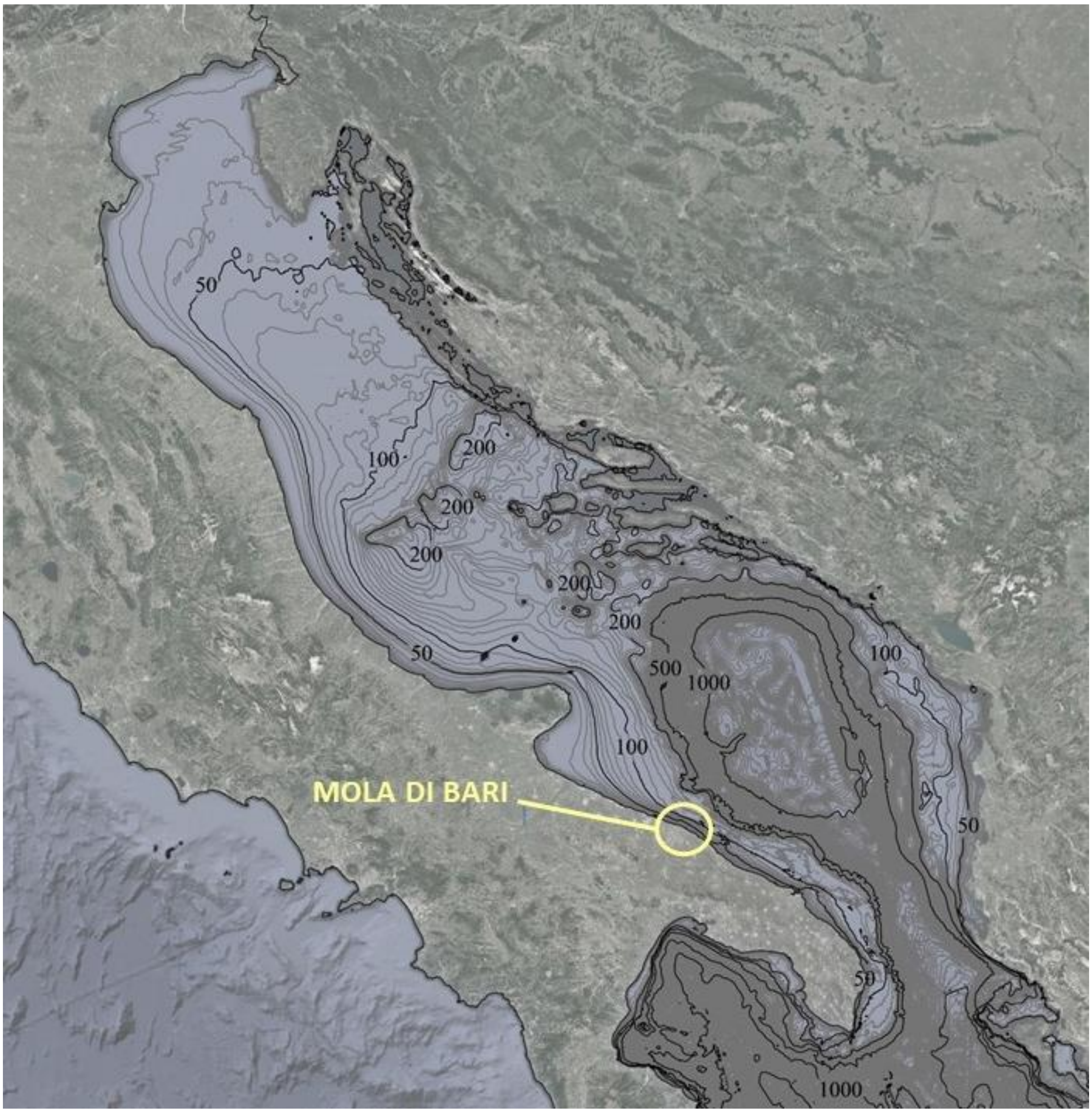

Figure 1. Bathymetry of the Adriatic Sea and location of Mola di Bari.

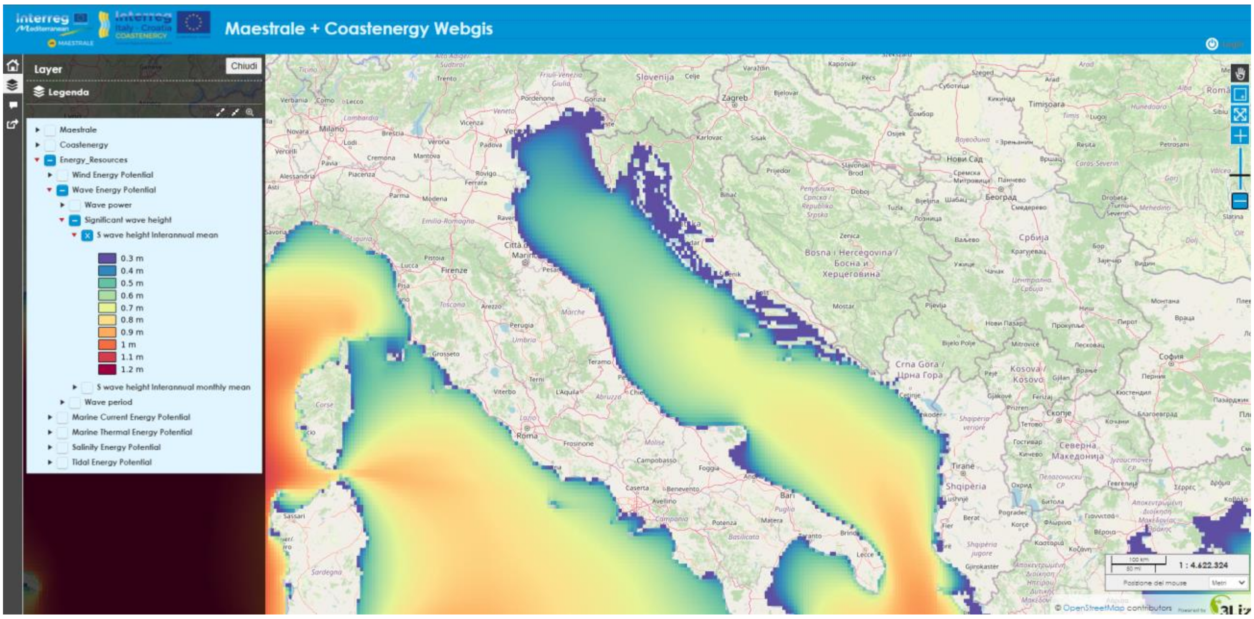

Figure 2. Map of wave height interannual means in the Adriatic Sea (source: Maestrale + Coastenergy webGIS).

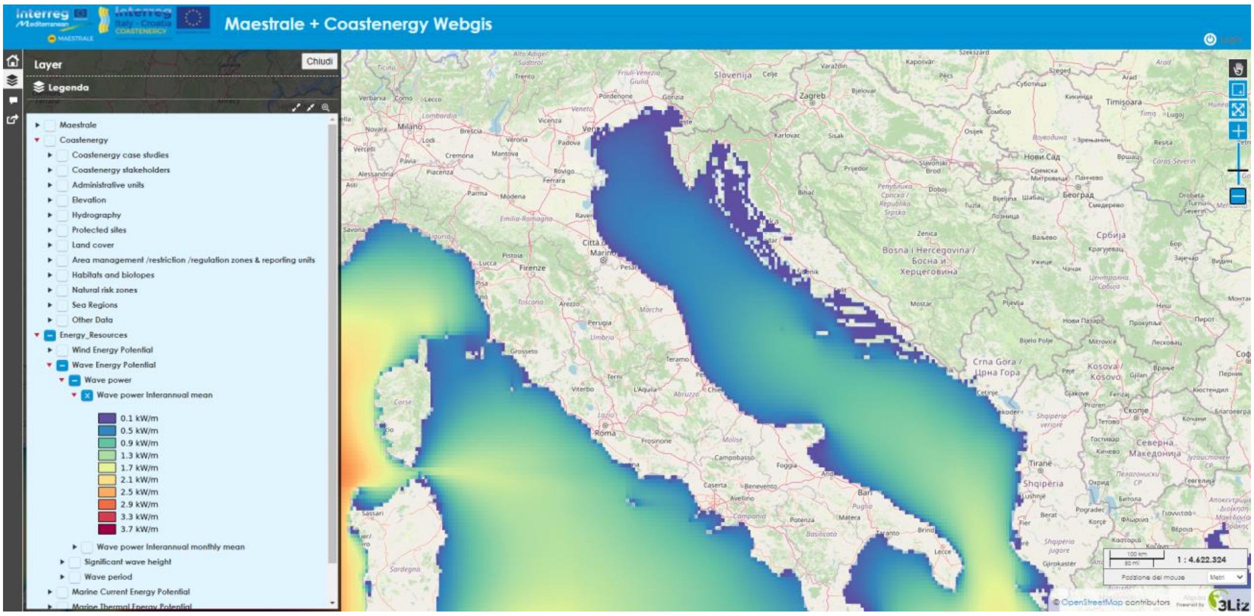

Figure 3. Map of wave power interannual means in the Adriatic Sea (source: Maestrale + Coastenergy webGIS).

The port of Mola di Bari has been chosen as pilot area for CMU's feasibility study because the municipal authority has since long been committed to regeneration and redevelopment programmes and plans for its port and waterfront areas, from the participation in the URBAN II initiative of the European Commission to more recent, currently undergoing, initiatives for waterfront redevelopment and the building of a floating district. The City of Mola is also involved in the Interreg Italy-Greece strategic project "AI Smart – Adriatic-Ionian Small Port Network", aimed at promoting the use of alternative energies and green solutions in maritime and intermodal transport and creating a cross-border network of small ports.

Figure 4. Past and ongoing initiatives by the City of Mola di Bari for the regeneration of the waterfront and port areas.

Figure 5. Past and ongoing initiatives by the City of Mola di Bari for the regeneration of the waterfront and port areas: waterfront regeneration financed by URBAN II (top); second set of waterfront regeneration (centre); floating district in the Great Port (bottom).

Mola di Bari has two distinct ports: Porto Piccolo (Small Harbour) and Porto Grande (Great Harbour), both consisting of two piers; the latter, located at approximately 41° 03' 34" N – 17° 05' 53" E, is object of this feasibility study. The western pier of Porto Grande, consisting of three stretches, is 600 m long, while the eastern pier, consisting of two stretches, is 700 m long.

Figure 6. The ports of Mola di Bari.

2 Selected technologies

Two wave energy converter technologies have been selected for the pilot area of Mola di Bari:

- ISWEC (Inertial Sea Wave Energy Converter) is an off-shore device consisting of a sealed floating hull containing a pair of gyroscopic systems. The pitching movement of the hull is intercepted by the two gyroscopes and transmitted to generators, which transform it into electric energy;
- OBREC (Overtopping Breakwater for Energy Conversion) is an on-shore device that can be integrated into an existing breakwater, or built in a new one. It is made of a concrete caisson with a front ramp and reservoir capturing the water from the incoming waves, which then flows through low-head turbines to produce energy.

2.1 ISWEC

ISWEC (Inertial Sea Wave Energy Converter) is the result of a research carried out by Politecnico di Torino and the Wave for Energy spin-off company, later on supported by ENI. It consists of a small boat to be moored in open waters – but not far from the coast – containing a gyroscopic system and an electric generator.

ISWEC is based on an inertial system exploiting wave motion: the waves cause a pitch of the hull that is transmitted to the generator placed along the roll axis via a flywheel mounted on a gyroscopic system. The machine can also be tuned – according to the variations in the state of the sea – by controlling the flywheel speed. Several prototypes have been developed; the data used for this study have been inferred based on the information available for the prototype deployed off Pantelleria.

Floater length	15 m
Floater width	8 m
Floater height	5 m
Rated power	100 kW
Mass	316 t
Ballast mass	200 t
Empty hull mass	56 t
Gyroscopic unit mass	30 t
Maximum flywheel speed	600 rpm
Annual productivity range	100-200 MWh
Estimated lifetime	20 yrs

Table 1. Main characteristics of the ISWEC prototype deployed off Pantelleria (source: Di Muro et al. 2021).

In this prototype, besides a free-air gyroscope, a second, vacuum-chamber gyroscope has been tested in order to minimise the energy losses caused by the rotation of the flywheel.
The prototype has a complex mooring system designed to prevent the anchors from sliding thanks to a "virtual seabed" system of chain stretches, floaters and counterweights able to dissipate the hull's pulling energy and avoid an excessive stress on the chains and connections (see Figures 24 and 25). A main mooring system (front mooring) is connected to the bow (Figure 24); a secondary mooring system (yaw mooring) is connected to the stern and allows keeping the floater oriented along the main wave direction (Mattiazzo et al. 2014). However, another description of the mooring system for this prototype (Vissio 2017) does not mention the secondary mooring system (Figure 25), describing the floater as being able to self-align with the wave direction.

Figure 7. The ISWEC prototype before being towed to Pantelleria (left), and at sea off the island (right) (source: Wave for Energy).

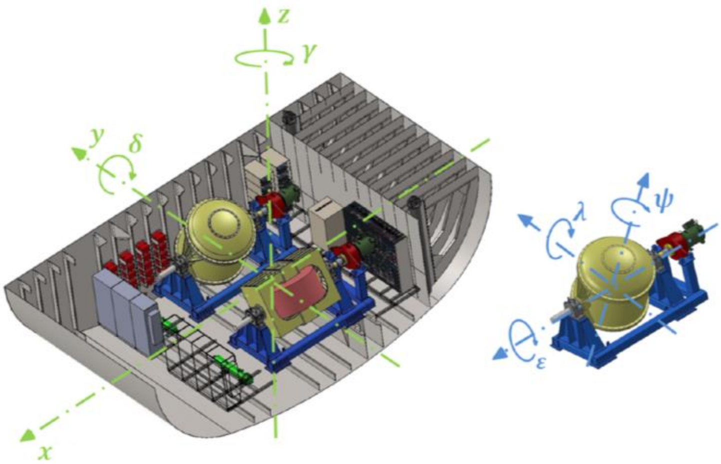

Figure 8. Scheme of the 100-kW prototype (source: Vissio 2017).

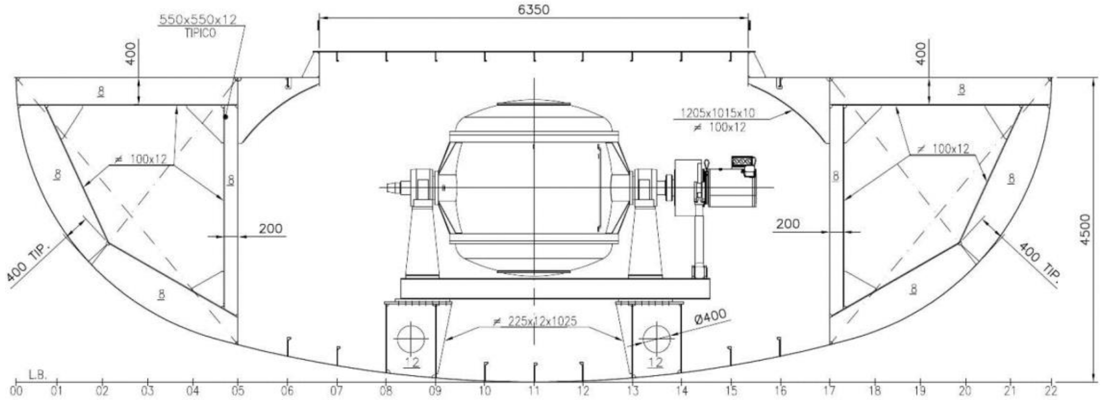

Figure 9. Cross section of the 100-kW prototype (source: Mattiazzo et al. 2014).

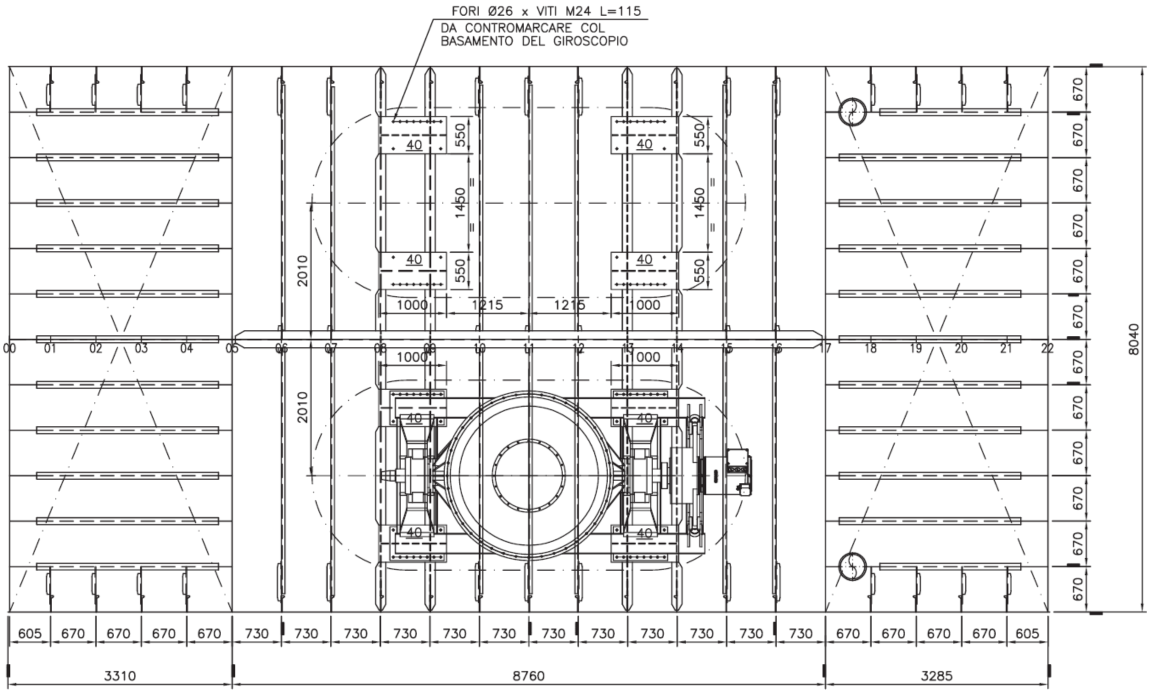

Figure 10. Plan of the 100-kW prototype (source: Cagninei et al. 2015).

Figure 11. Pictures of one of the gyroscope groups installed on the 100-kW prototype (source: Vissio 2017).

2.2 OBREC

OBREC (Overtopping Breakwater for Energy Conversion) is being developed by the University of Campania "Luigi Vanvitelli". It is conceived for partially substituting the rubble mounds of a traditional breakwater. A full-scale prototype has been built and tested in the port of Naples.

The device consists of a front reservoir designed to capture the waves overflowing an inclined ramp in order to convert their kinetic energy into potential energy. The water stored in the reservoir produces energy by flowing through low-head water turbines installed in a caisson, as a result of the difference in level between the reservoir and the main seawater level.

The data used for this study have been inferred based on the information available for the prototype deployed in Naples. This prototype is intended as a full-scale, 5-metre section of a prospective, operational device.

Length along seafront	5 m
Height	≈ 5 m
Concrete mass (reinforced concrete structure)	110 t
Iron mass (reinforced concrete structure)	7 t
Rated power	2.5 kW
Estimated yearly electricity production	12.6 MWh

Table 2. Main characteristics of the OBREC module prototype deployed at the port of Naples (source: Patrizi et al. 2019).

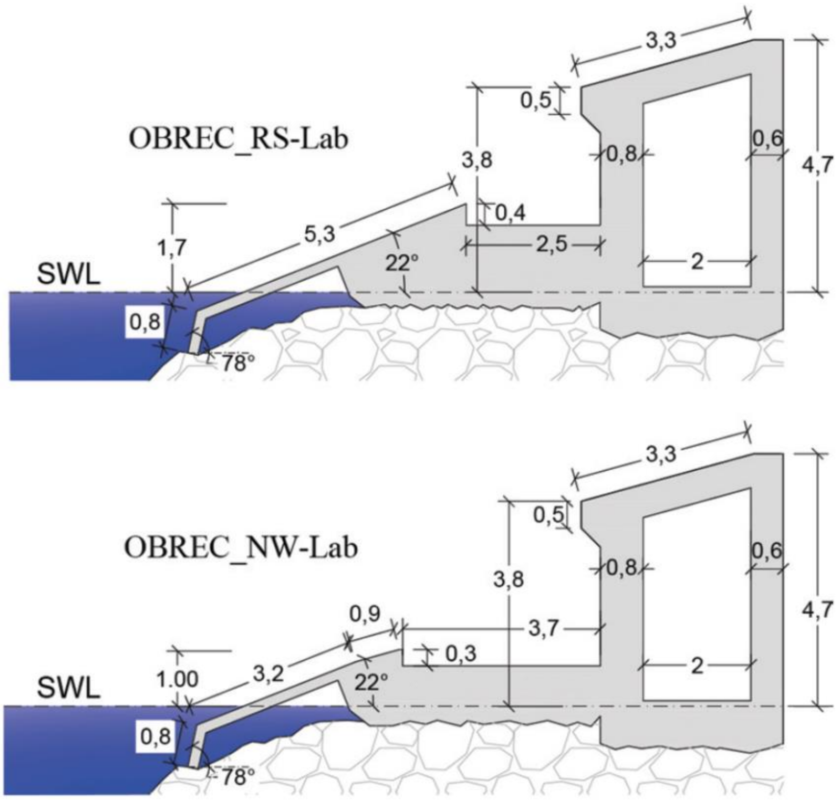

Figure 12. Cross-sections of the OBREC module prototype installed in Naples (source: Di Lauro et al. 2019). In order to test different operating conditions, the module has two parallel reservoirs at different heights.

Figure 13. OBREC prototype in the port of Naples (source: Contestabile et al. 2016). The two reservoirs with their respecrtive openings at different heights are clearly visible.

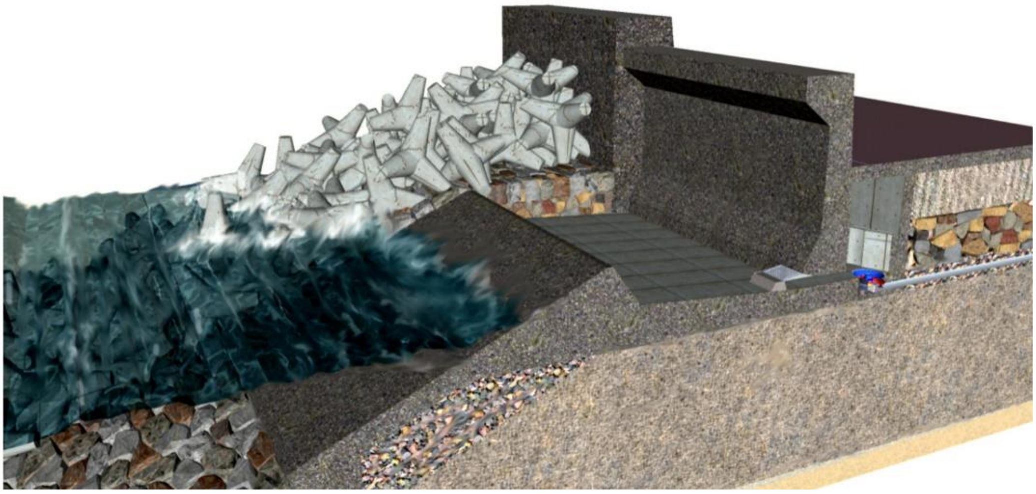

Figure 14. 3D model of a breakwater equipped with OBREC compared to a traditional rubble mound breakwater (source: Palma et al. 2014). The particular configuration at the top of the parapet in the OBREC-equipped breakwater is designed to minimise the water overflow at the back of the structure, compensating for the absence of the traditional rubble mound.

A cost analysis made in 2014 for a Master's degree thesis (Baldin 2014) has shown that if a new breakwater structure is shaped specifically to host an OBREC device (i.e., with a concrete ramp and a reservoir replacing part of the traditional rubble mound), it can cost less than a traditional breakwater. Another study (Vicinanza et al. 2014) demonstrated that such configuration can have a similar, if not better, hydraulic perfomance in terms of reduced overflow at the back of the structure, and similar or even lower reflection coefficients, if specific design conditions are met. Therefore, if a new breakwater is needed to protect a port basin, building it with this shape could be a no-regret solution providing additional benefits, independently from its energy productivity.

Descrizione intervento	€/m diga tradizionale
Mantellata	14978
Scogliera emersa	2395
Berma di sommità	2395
Strato di filtro	5574
II Strato di filtro	623
Nucleo	676
Parametro interno	3082
Opere di coronamento	8312
Costo totale	38033

Descrizione intervento	€/m **diga innovativa**
Mantellata	7099
rampa sommersa	1289
Berma sommersa	7092
Strato di filtro	2995
II Strato di filtro	365
Nucleo	647
Parametro interno	1199
Opere di coronamento	11380
Costo totale	32065

Figure 15. Unit cost comparison between a traditional rubble mound breakwater (left) and a breakwater equipped with concrete ramp and reservoir (right). Not considering the energy generators, the latter would cost about 6,000 €/m less (source: Baldin 2014).

3 Possible locations for the proposed plants

The proposed solution consists in the deployment of one or more ISWEC floaters off the port and the installation of an OBREC device in the western pier.
ISWEC could be deployed off the Greater Port, at a distance of about 2,000 m from the piers (see § 3.1), while OBREC could be installed in the second stretch of the western pier. A possible, additional location for OBREC could be the eastern pier, in order to harvest from the waves coming from the eastern quadrant as well (see § 3.2).

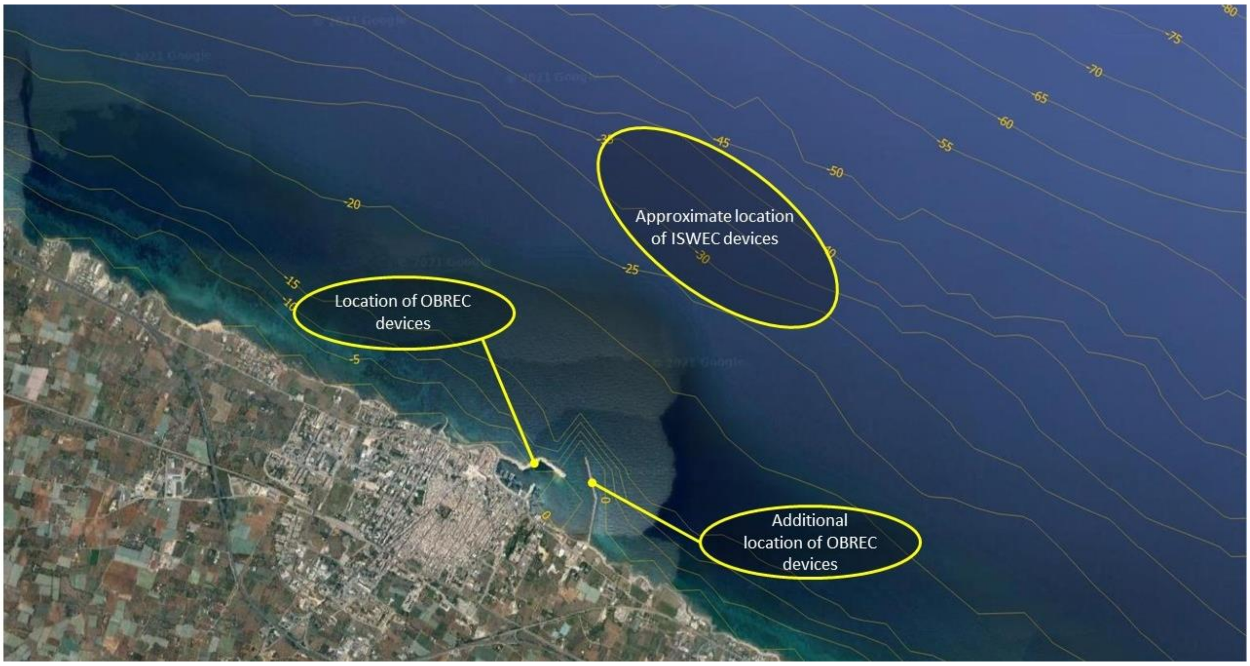

Figure 16. Possible locations for ISWEC and OBREC.

3.1 ISWEC

The sea depth allowing for an optimal functioning of an ISWEC floater depends on the local wave conditions. According to the information provided by Wave for Energy during one of the events connected to the Coastenergy project (see § 9.2, #8), ISWEC should be deployed before the point where the wave is about to break, which depends on the interaction between wave length/height and water depth, or the presence of obstacles on the seabed. Moreover, its optimal location should be identified based on detailed data about wave period and wave power density, which is usually available only after an ad-hoc monitoring campaign. Since this data is not available for Mola di Bari, we assume that a reasonable depth for the installation is similar to the one at the Pantelleria test site (between 30 and 35 m): this depth can be found at approximately 2,000 m from the coast of Mola, just beyond the boundary of the Natura 2000 site (see § 5.1). An installation in this area would therefore allow having a suitable depth and at the same time avoiding possible impacts on the protected Posidonia meadows and additional authorisation procedures.

3.2 OBREC

The closest buoy of the national wave monitoring network is located off Monopoli, about 20 km south of Mola (see § 9.2, #4). The charts in Figure 18 show the values of wave direction and height for every half hour between May and December (historical data is currently available only for the last eight months of 2021). The actual wave heights at the port of Mola are likely different from what detected at the Monopoli buoy, but this is the most detailed data available at the moment. Of course, an ad-hoc local monitoring campaign would be necessary in order to allow for a site-specific design of the device.
In order to highlight the wave direction with the highest occurrence, the related values have been categorised into sectors of 45°, as illustrated in the chart of Figure 19. The highest occurrence is clearly in the range from NW to NE (315° to 45°), accounting for more than half of the occurrences. Therefore, the western pier seems to be the most suitable for this kind of installation; the second stretch in particular is exposed to the waves coming from NW, which account for about 40% of the total occurrences.
A further consideration can be made about the relation between wave direction and height. In the period between October and December, when the wave height is higher, the wave direction is more evenly distributed between the northern and the eastern quadrants. As can be seen from the overlay of the wave direction and wave height charts for this period of the year (Figure 20), the highest waves are not necessarily those coming from the northern quadrant, but there are several cases when relatively high waves come from the eastern sector. Based on the characteristics and the design of the OBREC device, and on more specific local monitoring data that are not currently available, a further installation in the eastern pier could prove to be appropriate in order to exploit the waves coming from both directions.

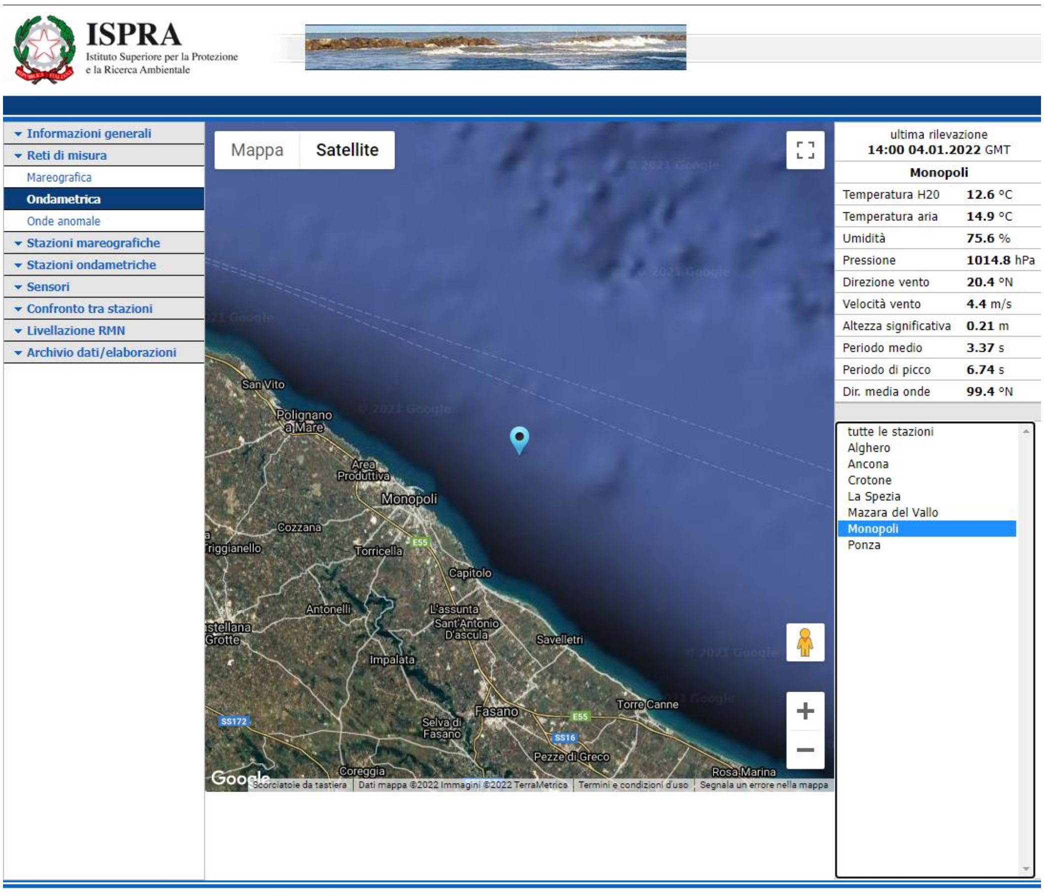

Figure 17. Monopoli wave buoy (source: ISPRA).

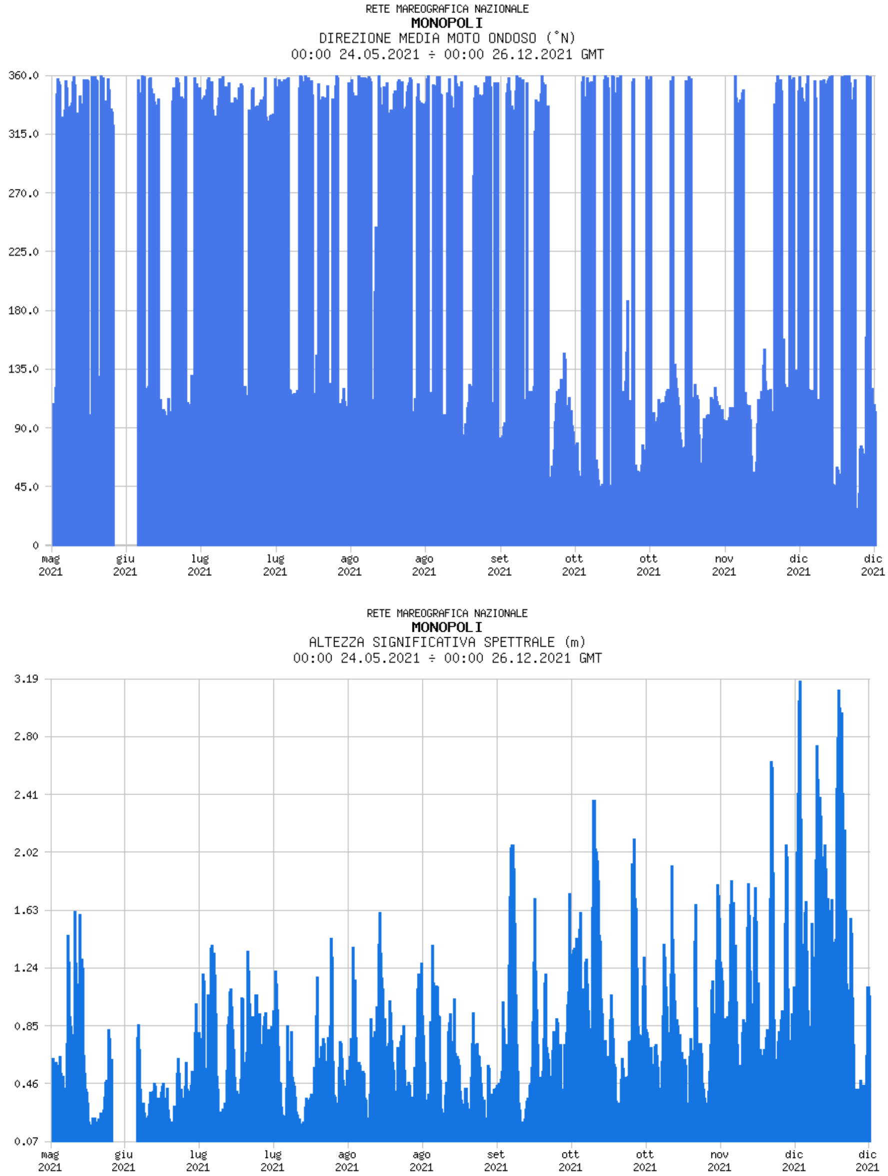

Figure 18. Wave direction (top) and height (bottom) at the Monopoli wave buoy form May to December 2021 (source: ISPRA). The relative occurrence of waves coming from the eastern quadrant increases in winter, along with the average wave height.

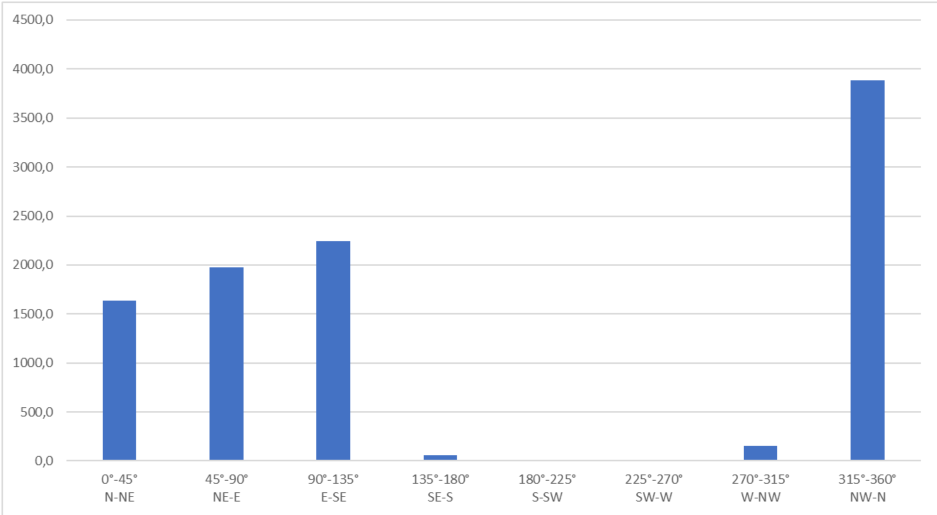

Figure 19. Occurrences of wave direction from May to December at the Monopoli wave buoy (own elaboration from ISPRA). Most of the waves come from the northern quadrant, i.e. between 315° and 45°.

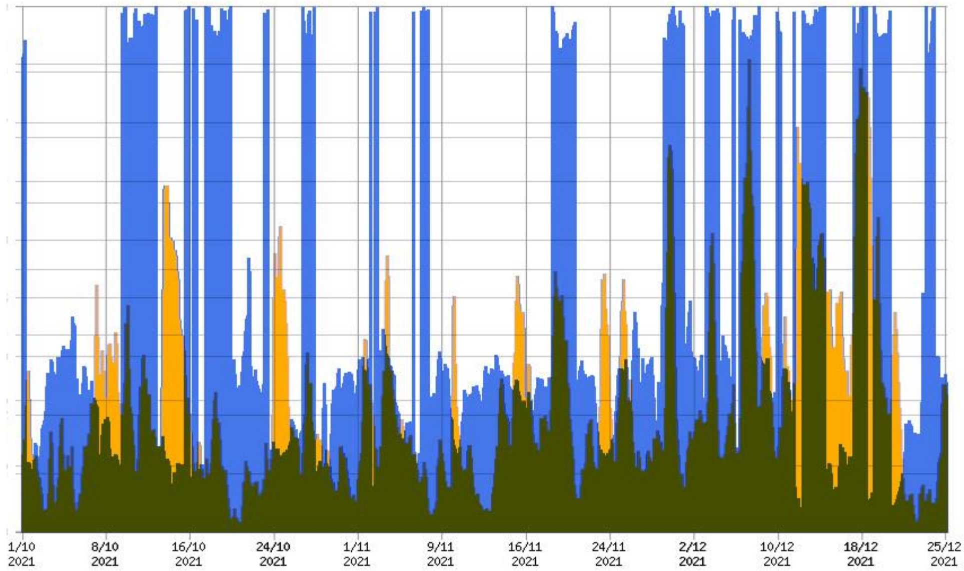

Figure 20. Overlay (green) of wave direction (blue) and height (orange) from October to December at the Monopoli wave buoy (own elaboration from ISPRA). Highest waves (above 2.5 m) come from the northern quadrant, but there is also a relevant occurrence of medium-height waves (1.5-2.5 m) coming from the eastern quadrant.

The proposed location for an OBREC device at the western pier, and a possible additional device at the eastern pier (see Figures 16 and 21), are based on preliminary considerations made starting from the wave climate data recorded by the nearest wave buoy (Monopoli). However, it must be noted that the bathymetry around the port of Mola is rather different from that of the port of Naples, where the OBREC prototype has been installed (see figure below). The wave height and behaviour at the point where the overtopping water is supposed to be catched might therefore be rather different, conditioning the overall performance of the device. A specific monitoring and analysis of the local waves is necessary in order to assess the actual feasibility of the device at this site, and adjust its design according to the local conditions.

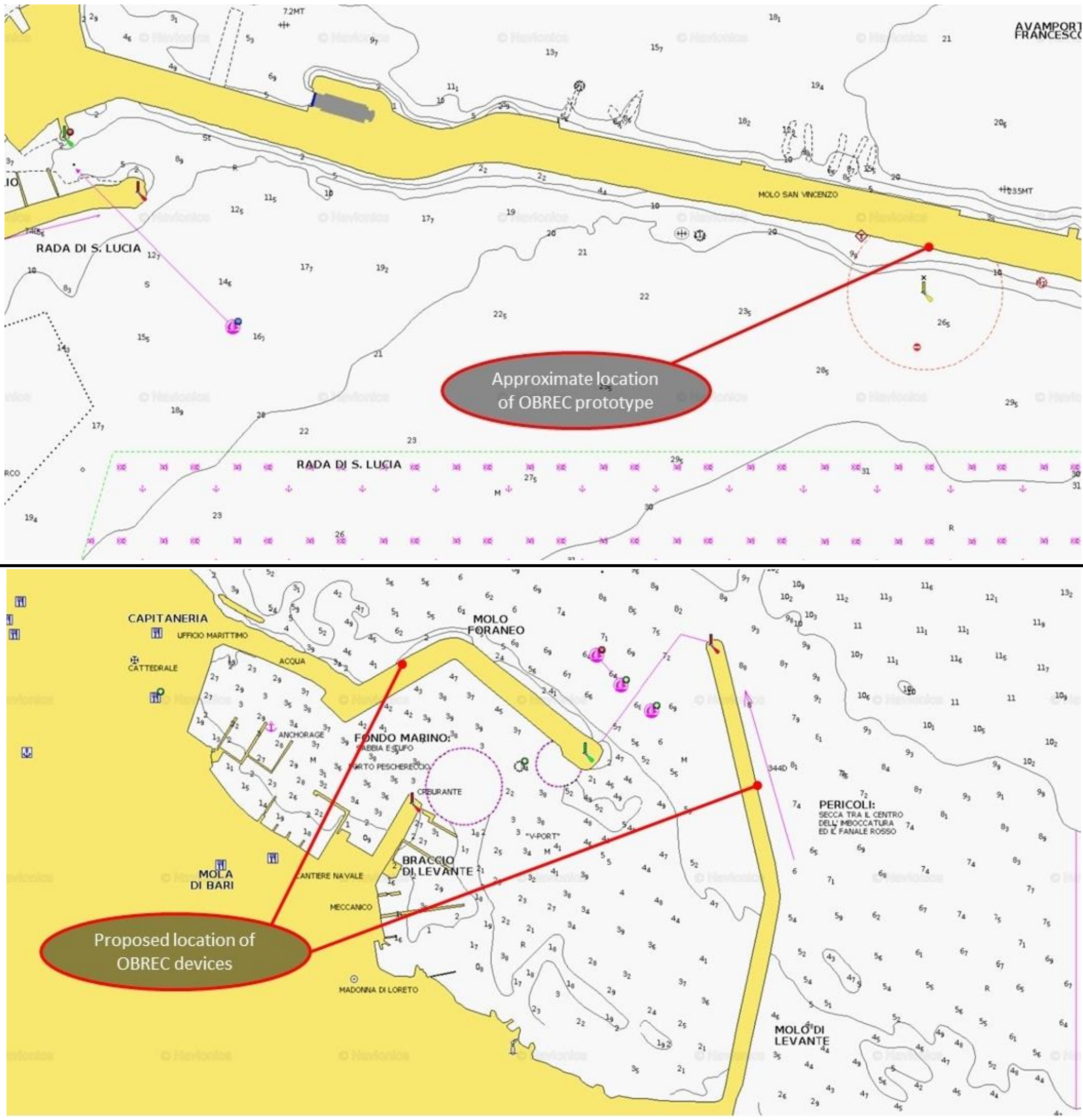

Figure 21. Comparison of bathymetries at the site of installation of the OBREC prototype in Naples (above) and the proposed locations in the pilot area (below) (source: Navionics). The seabed in front of the pier in the port of Naples has a steeper configuration.

4 Energy production, emissions saved, and considerations on the economic feasibility

Based on the information currently available, the amount of energy that can be produced by these devices at a certain location is difficult to estimate. On the one hand, there is poor and/or contrasting data in literature, since these technologies are still being tested and will need a considerable amount of time before being ready for a market application. On the other hand, both ISWEC and OBREC can by no means be considered one-fits-all solutions and their design needs to be carefully tuned for each specific site of operation. However, some considerations about their productivity are made below.

4.1 ISWEC

The ISWEC prototype analysed for the purposes of this study is the one tested off the coast of Pantelleria in 2015. It consists of a 15×8-metre, 316-ton floater designed to react to incoming waves with a pitching movement, and containing a 200-ton ballast and two 30-ton gyroscopic units composed of a flywheel, a gyro structure and a PTO, able to convert this movement to electricity, for a total rated power of 100 kW (Di Muro et al. 2021). Other prototypes have been and are being tested as well, with different sizes and characteristics.

The annual productivity range of this prototype is, according to Di Muro et al. (2021), between 100 and 200 MWh/y; this is quite consistent with the information provided by Wave for Energy during one of the events connected to the Coastenergy project (see § 9.2, #8), when a range between 100 and 150 MWh/y was declared, together with a cost of approximately 1,000,000 € for the tested prototype. We suppose that this figure includes the costs of the mooring system, but it is surely exclusive of the electrical connection to the island, since no connection was made during this testing campaign. Grassilli (2016) reports a range between 2.5 and 6 M€ per installed MW for an ISWEC farm; in this case, the cost of a single 100-kW device would be between 250,000 and 600,000 €, plus 10% for the mooring system, but this is an assumption related to a more mature development phase, when the costs will hopefully be reduced thanks to the optimisation of processes and technologies. A rough estimate of the costs for building and deploying such a device in the case of Mola is reported in the following tables for the worst-case (600,000 € per device) and best-case scenario (250,000 per device) as reported by Grassilli (2016).

	Works, equipment and services (1 floater)	Approximate cost for the worst-case scenario (€)
1	ISWEC floater with ballast and 2 gyroscopic units (Grassilli 2016)	600,000
2	Mooring system (≈10% of costs of floater unit) (Grassilli 2016)	60,000
3	Underwater cable (250 €/m × 2,000 m)	500,000
4	Unexpected costs (≈5% of works and equipment)	60,000
5	Surveys, design, supervision of works, authorisations, tests (≈15% of works and equipment)	175,000
6	Other costs related to administrative procedures	50,000
7	Decommissioning (≈1% of works and equipment) (Grassilli 2016)	10,000
	Total cost	**≈1,500,000**

Table 3. Indicative costs (worst-case scenario) for the installation of an ISWEC device off the port of Mola di Bari.

	Works, equipment and services (1 floater)	Approximate cost for the best-case scenario (€)
1	ISWEC floater with ballast and 2 gyroscopic units (Grassilli 2016)	250,000
2	Mooring system (≈10% of costs of floater unit) (Grassilli 2016)	25,000
3	Underwater cable (250 €/m × 2,000 m)	500,000
4	Unexpected costs (≈5% of works and equipment)	40,000
5	Surveys, design, supervision of works, authorisations, tests (≈15% of works and equipment)	115,000
6	Other costs related to administrative procedures	50,000
7	Decommissioning (≈1% of works and equipment) (Grassilli 2016)	8,000
	Total cost	**≈1,000,000**

Table 4. Indicative costs (best-case scenario) for the installation of an ISWEC device off the port of Mola di Bari.

The above estimates do not take into account the costs for maintenance. The overall operational expenditure (OPEX) is estimated by Grassilli (2016) to be 2.5% of the capital expenditure per year; in this case it would be about 40,000 €/y for the worst-case scenario and 25,000 €/y for the best-case scenario. The worst-case scenario is very far from being convenient in terms of payback time. Only considering the best-case scenario and installing 10 devices in order to optimise the costs of the underwater cable, we obtain a total cost of about 4 M€ and a payback time of about 20 years.

	Works, equipment and services (10 floaters)	Approximate cost for the best-case scenario (€)
1	10 ISWEC floaters with ballast and 2 gyroscopic units (Grassilli 2016)	2,500,000
2	Mooring system (≈10% of costs of floater unit) (Grassilli 2016)	250,000
3	Underwater cable (250 €/m × 2,000 m)	500,000
4	Unexpected costs (≈5% of works and equipment)	165,000
5	Surveys, design, supervision of works, authorisations, tests (≈15% of works and equipment)	490,000
6	Other costs related to administrative procedures	50,000
7	Decommissioning (≈1% of works and equipment) (Grassilli 2016)	35,000
	Total cost	**≈4,000,000**

Table 5. Indicative costs (best-case scenario) for the installation of 10 ISWEC devices off the port of Mola di Bari.

Under these circumstances, considering an annual energy consumption of 2.7 MWh for an average family (as reported by ARERA, the national authority regulating the energy market), a production of 1,500 MWh would cover the needs of 556 families. The cost of energy of 0.3 €/kWh is in line with what reported for the last quarter of 2021 by ARERA, when prices have dramatically increased caused by the geopolitical conditions (see § 9.2, #1).

According to Caputo (2021), the CO_2 emission factor of the overall gross thermal power production in Italy was 462.2 g CO_2/kWh in 2019. A production of 1,500 MWh/y would therefore save about 693 t CO_2/y.

Cost of works, equipment and services (€)	≈4,000,000
Yearly energy production (kWh)	1,500,000
Cost of energy (€/kWh)	0.3
Yearly revenue from energy production (€)	450,000
Yearly maintenance costs (€)	250,000
Net yearly revenue (€)	200,000
Payback time (years)	**≈20**
Families served	**556**
CO_2 emissions saved (t CO_2/y)	**693**

Table 6. Indicative payback time and emissions saved for 10 100-kW ISWEC devices deployed 2,000 m off the port.

The above figures are of course very indicative. The ISWEC technology is still in its development phase and will have to undergo many tests and improvements before being ready for the market. According to Grassilli (2016), as of 2016 the ISWEC team had set a target of reducing the CAPEX by more than 50% in 5 years. A new testing campaign off Pantelleria is currently being organised, but more recent information about costs and technological improvements is not currently available.

4.2 OBREC

The OBREC prototype analysed for the purposes of this study is the one tested in Naples starting from 2015. It consists of a 5-6 m long reinforced concrete module called DIMEMO (Diga Marittima per l'Energia dal Moto Ondoso), fitted with 3 low-head Kaplan turbines for a total power of 2.5 kW (Di Lauro et al. 2018). Other studies by the same researchers working in Naples are available, concerning the possible use of similar devices on the Australian and Chilean coasts (Contestabile et al. 2016, Mariani et al. 2021), but they have not been taken into account since the wave climates of such locations are very different from those existing in the Mediteranean.

The OBREC prototype tested in Naples could be "extended" along 100 m of one or more of the existing breakwaters in the port of Mola, creating a single reservoir connected to two or three turbines of adequate size for the production of energy. This type of installation is described for example in Baldin (2014) for the coast of Alghero: a 100-m device with 3 screw turbines with a nominal power of 62 kW and a maximum capacity of 5 m^3/s each, equipped with gates, spin multipliers, generators, power factor correction units, transformers, technical room, and auxiliary services controlling water levels, malfunctions, deteriorations, emergencies, etc. In this case, the cost of the OBREC device, including all the equipment and works for the power generation and excluding the works for building the structure of the modified breakwater, is estimated to be about 800,000 €. A rough estimate of the costs for building such a device in the case of Mola is reported in the following table.

	Works, equipment and services	**Approximate cost (€)**
1	Partial removal of rubble mound elements and their repositioning in suitable locations, to make room for the OBREC structure	50,000
2	Construction of reinforced concrete foundations, ramp, reservoir and caisson	800,000
3	Turbines, technical room, electrical components, cables, controls, gates and grids, assembly (Baldin 2014)	800,000
4	Unexpected costs (≈5% of works and equipment)	85,000
5	Surveys, design, supervision of works, authorisations, tests (≈15% of works and equipment)	250,000
6	Other costs related to administrative procedures	50,000
	Total cost	**≈2,000,000**

Table 7. Indicative costs for the installation of an OBREC device along 100 m of one of the existing breakwaters in the port of Mola di Bari.

The above estimate does not take into account the costs for maintenance and removal. The maintenance costs are estimated by Baldin (2014) to be 10,000 €/y, plus 10,000 € of extraordinary maintenance in the 7^{th} year, plus 5,000 €/y of unexpected expenses.
The analysis made by Baldin (2014) refers to the construction of a new breakwater equipped with a 100 m OBREC device in Alghero (Sardinia), able to produce (according to his calculations) 594 MWh/y. Under these conditions, and considering a subsidised (as of 2012) feed-in tariff of 0.3 €/kWh, the payback time would be between 5 and 6 years. However, such figures imply that the costs for the construction of the modified breakwater – including the ramp, reservoir and caisson – are not taken into account, starting from the consideration that it is an indispensable piece of infrastructure that would have been built in any case. Baldin (2014) assumes that, since the hydraulic performance of the modified breakwater is similar to that of a traditional breakwater, its construction with such configuration would make sense even if no energy is produced; this would not be applicable to the proposed case of Mola, where the installation of the OBREC in the existing breakwater would imply considerable works for its modification, ascribable to energy production purposes only, as shown in Table 7. Moreover, a productivity of 594 MWh/y is probably far too high for the local wave climate, which is much milder compared to Alghero. We can very indicatively assume that the productivity of an OBREC device in Mola is directly proportional to what described by Patrizi et al. (2014), i.e. 12.6 MWh/y for a 5 m module: for a 100 m installation, the production would be 252 MWh/y only. Therefore, the cost of such an installation would require many more years to be recovered.
Conversely, if the current commitments by the City of Mola to build a “floating district” are met, the OBREC device could be split in two parts, to be built in the new stretches of breakwater (about 50 m each) needed for the expansion of the port, as shown in Figure 22; these new stretches would be an extension of the western pier and would be oriented in the same direction as its second stretch, being exposed to the most recurrent waves. Under these circumstances, the costs for building and installing the OBREC devices would be shared with the costs for bulding the new, double-purpose breakwaters, and the payback time (16.5 years) would consequently be more reasonable.

	Works, equipment and services	Approximate cost (€)
1	Turbines, technical room, electrical components, cables, controls, gates and grids, assembly (Baldin 2014)	800,000
2	Unexpected costs (≈5% of works and equipment)	40,000
3	Surveys, design, supervision of works, authorisations, tests (≈15% of works and equipment)	120,000
4	Other costs related to administrative procedures	50,000
	Total cost	**≈1,000,000**

Table 8. Indicative costs for the installation of an OBREC device along 100 m of new breakwater stretches in the port of Mola di Bari.

The energy produced could be used for partially covering the needs of the floating district: considering an annual energy consumption of 2.7 MWh for an average family (as reported by ARERA, the national authority regulating the energy market), a production of 252 MWh would cover the needs of 93 families. The cost of energy of 0.3 €/kWh is in line with what reported by for the last quarter of 2021 by ARERA, when prices have dramatically increased caused by the geopolitical conditions (see § 9.2, #1).
According to Caputo (2021), the CO_2 emission factor of the overall gross thermal power production in Italy was 462.2 g CO_2/kWh in 2019. A production of 252 MWh/y would therefore save about 116 t CO_2/y.

Cost of works, equipment and services, excluding points 1 and 2 in Table 7 (€)	≈1,000,000
Yearly energy production (kWh)	252,000
Cost of energy (€/kWh)	0.3
Yearly revenue from energy production (€)	75,600
Yearly maintenance costs (€)	15,000
Net yearly revenue (€)	60,600
Payback time (years)	**≈16.5**
Families served	**93**
CO_2 emissions saved (t CO_2/y)	**116**

Table 9. Indicative payback time and emissions saved for two 50-m OBREC devices built in new breakwaters.

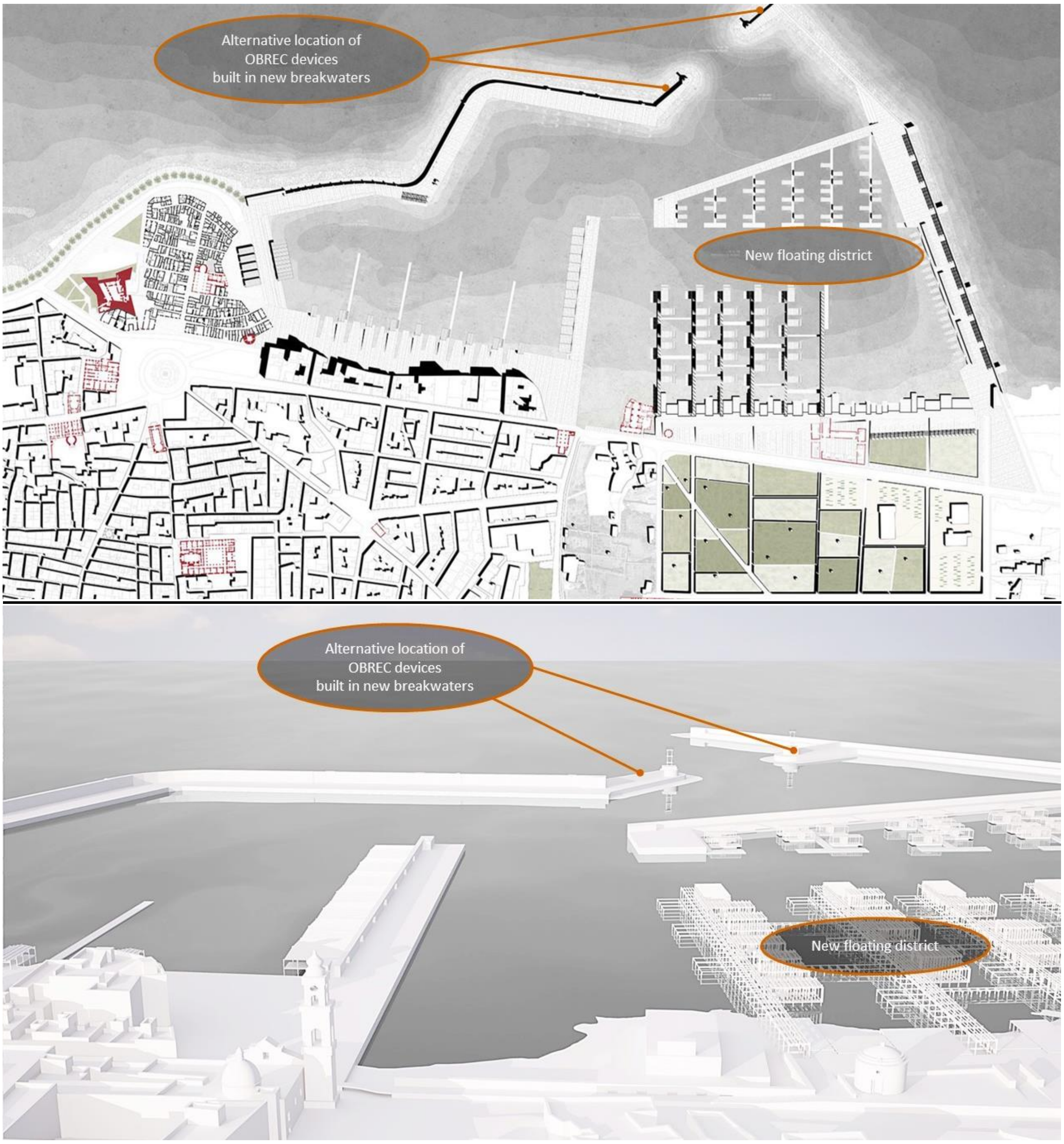

Figure 22. Alternative location for the OBREC devices (source: Michele Montemurro). Their integration in new breakwaters planned for protecting a port expansion would allow to save on costs.

5 Environmental and landscape impacts

5.1 Environmental restrictions

There is a marine Special Area of Conservation (SAC) along this stretch of coast (IT9120009 – Posidonieto San Vito-Barletta), aimed at the protection of the Posidonia meadows growing on the seabed. It has a width of about 2 km starting from the shore line.

The following considerations can be made for the chosen technologies:

- since ISWEC should be deployed at a distance of at least 2 km from the coast in order to meet the minimum depth requirements for its operation, the mooring system would not interfere with the SAC (see picture below). However, the cable for the electrical connection, to be laid on the seabed, would cross the Posidonia meadows before reaching the mainland. Therefore, an Appropriate Assessment would be needed for the authorization of the works, as requested by the Habitats Directive. An Appropriate Assessment might be required even for the mooring system, since it would be located in the vicinity of the border of the SAC;
- a deployment of up to 10 100-kW ISWEC devices would not be subject to EIA screening, since it would fall under the category of "non-thermal industrial plants for the production of energy, steam and hot water" not exceeding 1 MW (Legislative Decree 152/2006);
- the existing western pier where OBREC would be installed is located just outside the borders of the SAC. In this case also, there is likely no relevant impact on the Posidonia meadows; however, even in this case an Appropriate Assessment might be required, since the devices would be located in the vicinity of the border of the SAC. On the contrary, the additional device in the eastern pier, and the ones to be built in the new piers protecting the floating district, would be subject to Appropriate Assessment, since they would fall inside the SAC;
- OBREC would not be subject to EIA, unless it is part of a newly built pier; in the latter case it would fall – together with the pier itself – under the category of "coastal works for protection against erosion and works aimed at modifying the coastal lines", being therefore subject to EIA (under a special procedure integrating EIA and the Appropriate Assessment mentioned above). The construction of a traditional pier/breakwater would in any case be subject to EIA and Appropriate Assessment, with or without an integrated OBREC.

There is no other protected area near the site of the proposed installations.

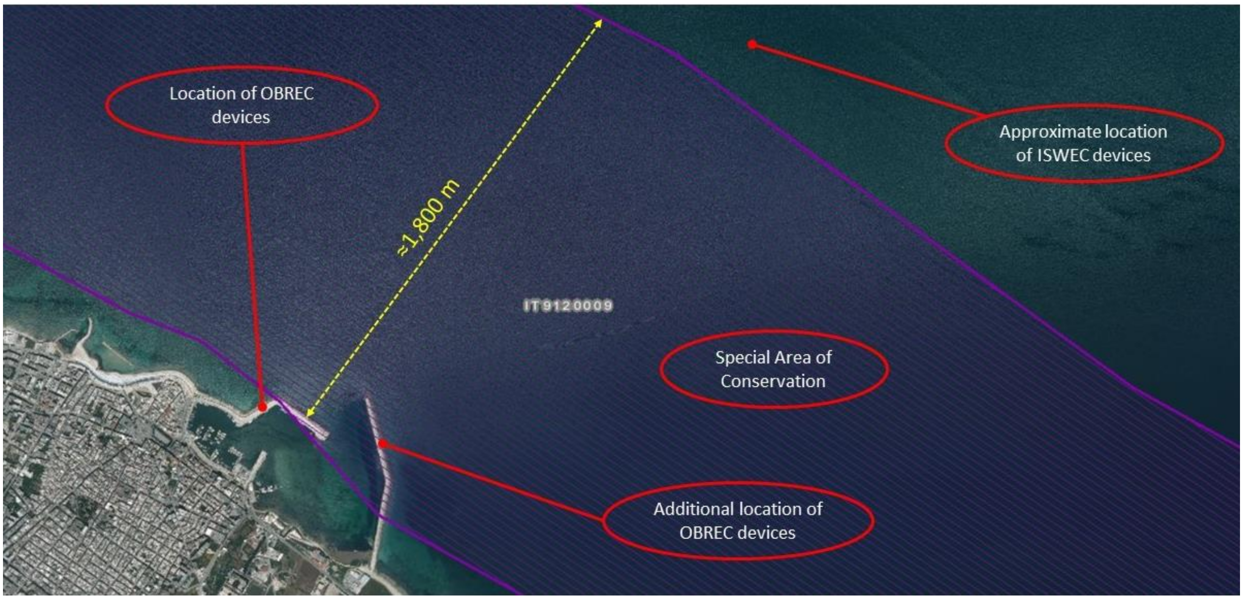

Figure 23. Natura 2000 site SAC IT9120009 – Posidonieto San Vito-Barletta (source: Geoportale Nazionale) and possibile locations of energy production devices.

5.2 Other environmental impacts

5.2.1 ISWEC

The mechanical and electrical parts allowing ISWEC to produce electricy are all placed inside the hull in a dry environment. This minimises any risk of contamination of the marine environment by possible spills of fluids or erosion of plastic and metal parts; it also minimises the diffusion of noises outside of the hull. However, the possible impacts should be carefully assessed and monitored in the future research and development phases.

Some assessments have been already made, yet with partial results, on the Pantelleria test site in 2015 and 2016. Their results are shortly illustrated below.

The ISWEC prototype in Pantelleria has been loosely moored to the seabed by means of several anchors connected to a special system able to dissipate the pulling energy exerted by the hull. Theoretically, such system prevents the anchors from sliding on the seabed and producing impacts on the benthos and sediments. A double monitoring campaign – before and after the deployment of the prototype in Pantelleria – has been made by ENEA and Politecnico di Torino by means of both in situ and remote sensing methods in order to assess the impacts of the anchors on the Posidonia meadows. The results are only partial, but the authors declare that the maps of Leaf Area Index for the Posidonia do not show a significant discontinuity and reduction in the proximity of the deployed prototype (Borfecchia et al. 2016, Borfecchia et al. 2021). In any case, the proposed area for the deployment of the ISWEC devices off the port of Mola is outside the border of the Natura 2000 site established to protect the local Posidonia meadows. Possible interferences with other benthonic life is minimised thanks to ISWEC's specially designed mooring system.

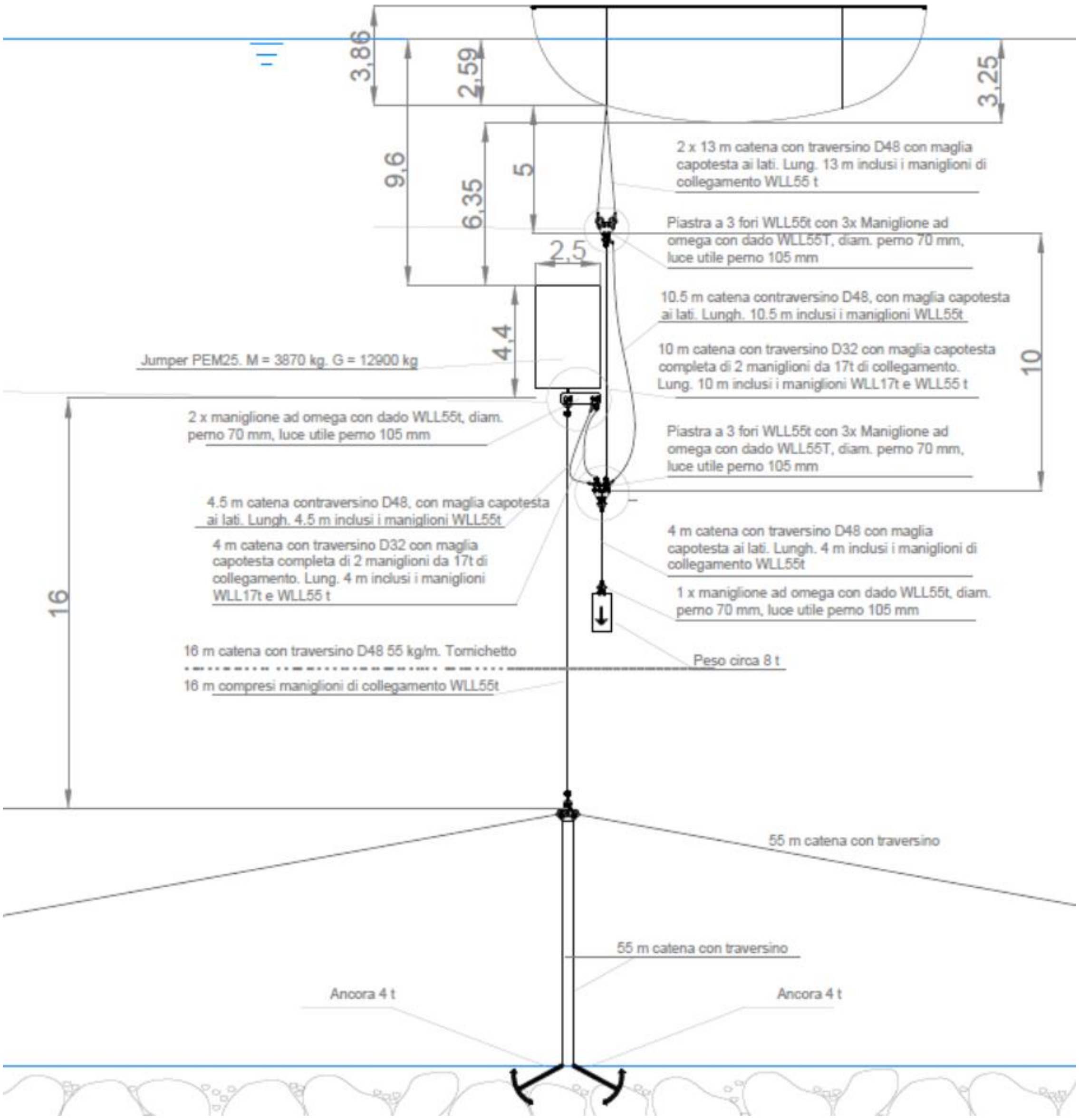

Figure 24. Scheme of the main mooring system for the ISWEC prototype deployed off Pantelleria (source: Mattiazzo et al. 2014).

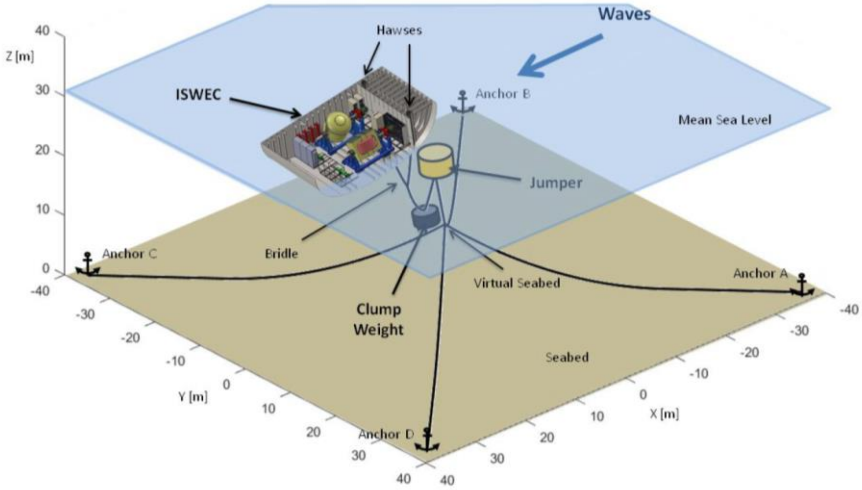

Figure 25. Scheme of the mooring system for the ISWEC prototype deployed off Pantelleria (source: Vissio 2017).

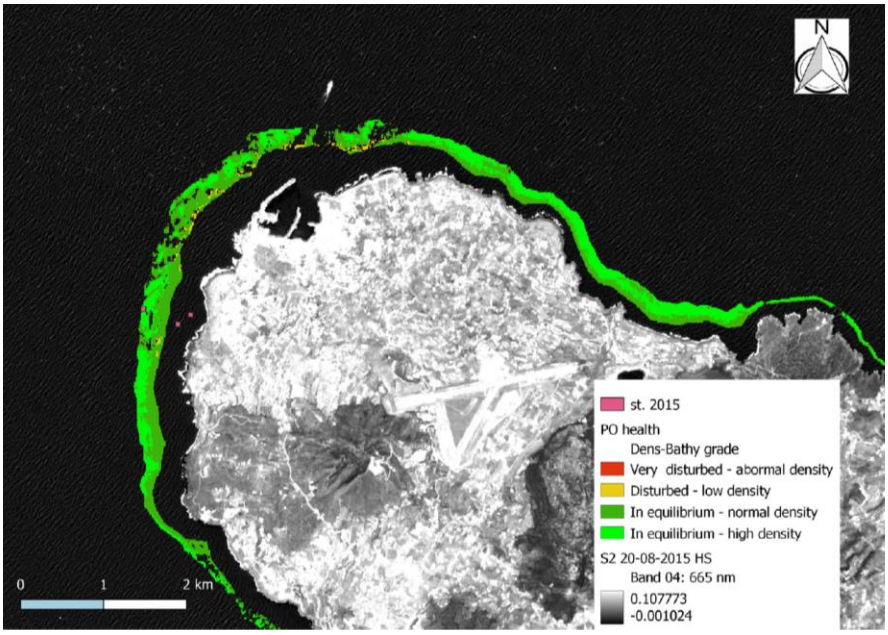

Figure 26. Classes of health of the Posidonia meadows along the coast of Pantelleria as assessed by Borfecchia et al. 2021.

The Pantelleria testing site has also been subject to monitoring of parameters related to hydrology, nutrients and contamination by heavy metals. The monitoring campaigns have been implemented by CNR before and after the deployment of the ISWEC. The authors were interested in particular to possible contaminations by metals released by the hull and mooring system. In this case also, there are no definitive results, but the changes detected in the parameters are attributed by the authors to the internal variability of the local marine environment rather than to a contamination by the deployed prototype (Placenti et al. 2017).

CNR, Politecnico di Torino and other universities have made an assessment of the acoustic impact of the ISWEC prototype in the Pantelleria test site. The noise has been analysed in four different conditions: before the installation, during the installation, after the installation, and during operation. The authors conclude that noises from the ISWEC exceed those of the local acoustic environment especially at lower frequencies and especially while in operation, and that the noise increases with wave height and flywheel speed. These effects have been estimated having a 1,000 m radius. The noise is produced by the vibrations of the hull and the anchoring system, and by the movement of the mechanical parts. Even if the power spectral density measured for a vessel passage is much more intense at all frequencies, and if there is still not enough information about the possible impact of noises on the perception of conspecific sounds in fish populations, the authors suggest to make improvements in the anchoring system and in the bearings of the moving parts, as well as to plan interruptions in the operation of the device in order to prevent possible masking of fish choruses during dusk in the summer season, which could correspond to courtship and spawning time (Buscaino et al. 2019).

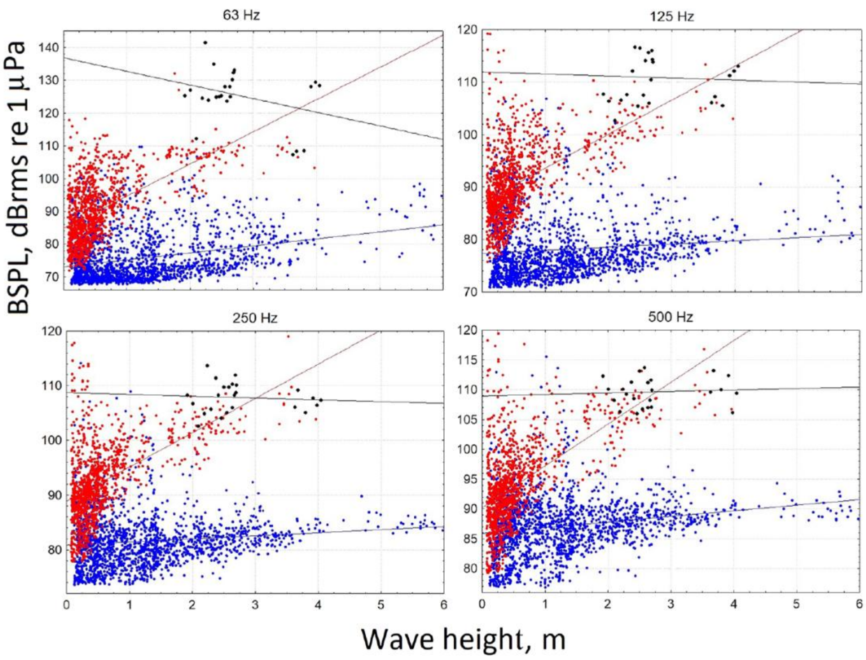

Figure 27. Some examples of scatter plots for band sound pressure level (BSPL) versus wave height at different frequencies recorded at the Pantelleria test site. Blue = before installation; red = after installation; black = during operation (source: Buscaino et al. 2019).

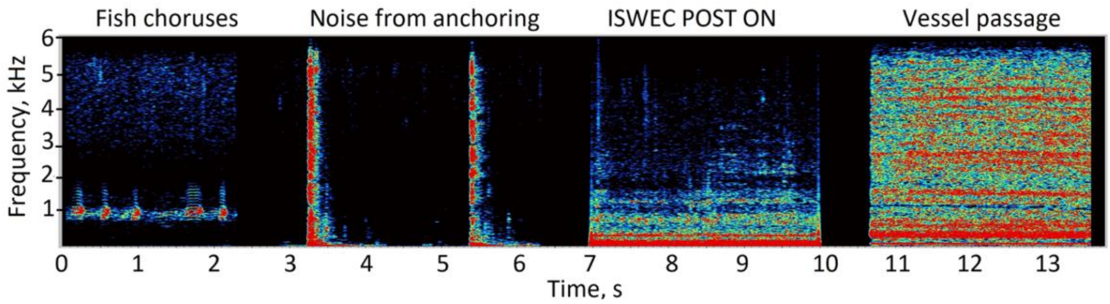

Figure 28. Spectrogram of sounds from fish choruses, noise from the anchoring system after installation, noise from the operating ISWEC, and noise from a vessel passage recorded at the Pantelleria test site (source: Buscaino et al. 2019).

5.2.2 OBREC

There are no studies on the environmental impacts of the OBREC system, excluding the Life Cycle Assessment reported by Patrizi et al. in 2019 (see § 5.3.2).
It is supposed that the device has no additional environmental impact compared to that of a traditional breakwater, which is intended to partially substitute; one typical impact of a breakwater is for example the artificial accumulation of sediments causing effects of erosion downstream along the coast. However, specific studies should be made on the possible impacts on marine life (e.g. fishes or other animals caught in the reservoirs), and the possible acoustic impacts (caused e.g. by the water falling towards the turbines and flowing through the pipes towards the rear of the structure). The results of such studies could help in designing solutions for mitigating the impacts, e.g. an escape channel for the animals or a different shape of the pipes to dampen the noise.

5.3 Life Cycle Assessment

5.3.1 ISWEC

A Life Cycle Assessment of the ISWEC prototype deployed at the Pantelleria site has been made by Politecnico di Torino (Di Muro et al. 2021). The inventory analysis has been made on the hull, vacuum chamber and free-air gyroscope, cooling system, electric system, main mooring, and aft mooring. The lifetime of the device has been assumed to be 20 years.
Most of the impacts are related to the steel components and are generated in the construction phase; an important contribution to the overall impacts regards the ozone depletion in the decommitment phase. The authors declare that ISWEC has a good environmental sustainability compared to other renewable

energy technologies: for example, polycrystalline silicon PV are reported to have a carbon intensity of 32 g CO_2eq/kWh, which is very close to the estimated performance of the ISWEC in its best-case scenario (i.e. 200 MWh/y of energy production); the carbon intensity of the worst-case scenario is also rather positive, being comparable with that of nuclear reactors. The following table shows the energy and environmental performance indicators calculated by the authors.

	100 MWh/y scenario	200 MWh/y scenario	Unit
Energy intensity	494.8	989.6	kJ/kWh
Energy payback	33	67	months
Carbon intensity	31.46	62.91	g CO_2eq/kWh
Carbon payback	18	40	months

Table 10. Findings of the LCA of the ISWEC prototype deployed off Pantelleria (source: Di Muro et al. 2021).

5.3.2 OBREC

A report on the Life Cycle Assessment of the OBREC prototype deployed at the harbour of Naples has been pubished by Patrizi et al. in 2019. The authors assume an average electricity production of 12.6 MWh/y for a single, 5-m long OBREC module. The decommitment phase has been excluded from the assessment, since the OBREC is meant to substitute the concrete cubes or tetrapods used in breakwaters, which should be removed in any case at the end of their lifetime. The main components analysed are foundations, ramps and reservoirs, pipes, PTO system, and electrical connections. The impacts of the construction and maintenance phase have been assessed as well. The lifetime of the device has been assumed to be 60 years.

The total carbon footprint of the module is 1.08 t CO_2eq. It is mainly caused by construction elements (884.31 kg CO_2eq), while minor contributions are provided by building operations (85.28 kg CO_2eq) and maintenance (113.57 kg CO_2eq). 82% of the total carbon footprint is related to the building materials, and 56% is caused by the concrete and iron needed for the foundations and caisson, which account for 95% of the total mass of the module. However, since an OBREC module would substitute an amount of concrete breakwater elements with a similar mass, the authors declare that these impacts should not be taken into account. Based on these considerations, the total carbon footprint of an OBREC module substituting part of a breakwater structure would be 0.48 t CO_2eq only.

Based on the same considerations, the carbon intensity of the electricity produced by an OBREC module has been calculated as 37 g CO_2eq/kWh (by comparison, the carbon intensity of a hydroelectric reservoir is about 10 g CO_2eq/kWh, and that of the Italian electricity grid mix is 578 g CO_2eq/kWh). The emissions avoided yearly would be 6.20-6.81 t CO_2eq, and the carbon payback time 13 months.

	12.6 MWh/y scenario	Unit
Carbon footprint	0.48	t CO_2eq
Carbon intensity	37	g CO_2eq/kWh
Emissions avoided	6.81	t CO_2eq/y
Carbon payback	13	months

Table 11. Findings of the LCA of the OBREC prototype installed at the port of Naples (source: Patrizi et al. 2019).

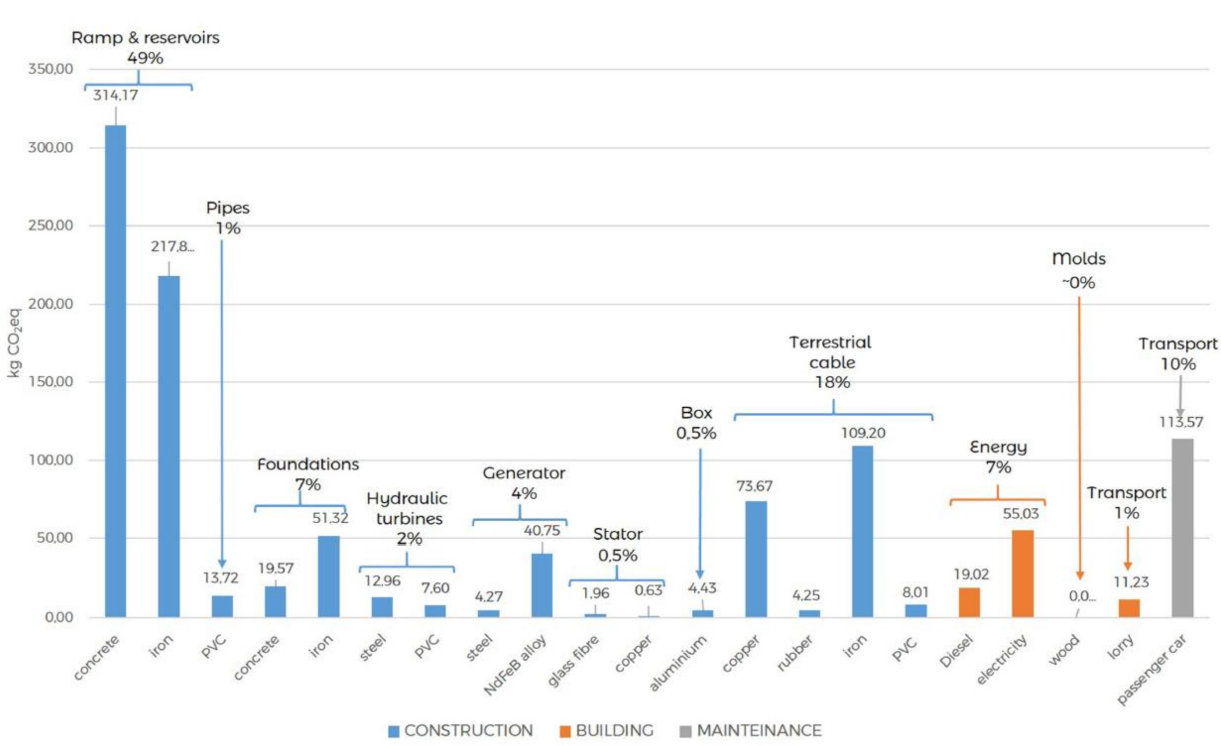

Figure 29. Breakdown of the carbon footprint of the OBREC prototype installed at the port of Naples (source: Patrizi et al. 2019).

5.4 Landscape restrictions and possible landscape impacts

As regards landscape restrictions, the OBREC installation would fall within a coastal area; therefore, according to the national Legislative Decree 42/2004 protecting certain classes of landscape assets (including a strip of land of 300 metres along all marine coasts), it would be subject to a "landscape authorisation" to be issued by the relevant offices of the Ministry of Culture or by a delegate municipal office (see picture below). The specific procedures and possible derogations are provided for by the norms of the Apulian Regional Landscape Plan. Considering that the area is already occupied by an artificial harbour, no particular issue should arise in the authorisation procedure.

The following considerations can be made for the chosen technologies:

- the ISWEC devices have a very low visual impact, since they are similar to small boats moored at a distance of 2 km from the coast;
- the OBREC devices would be built in the existing pier, virtually excluding any additional visual impact.

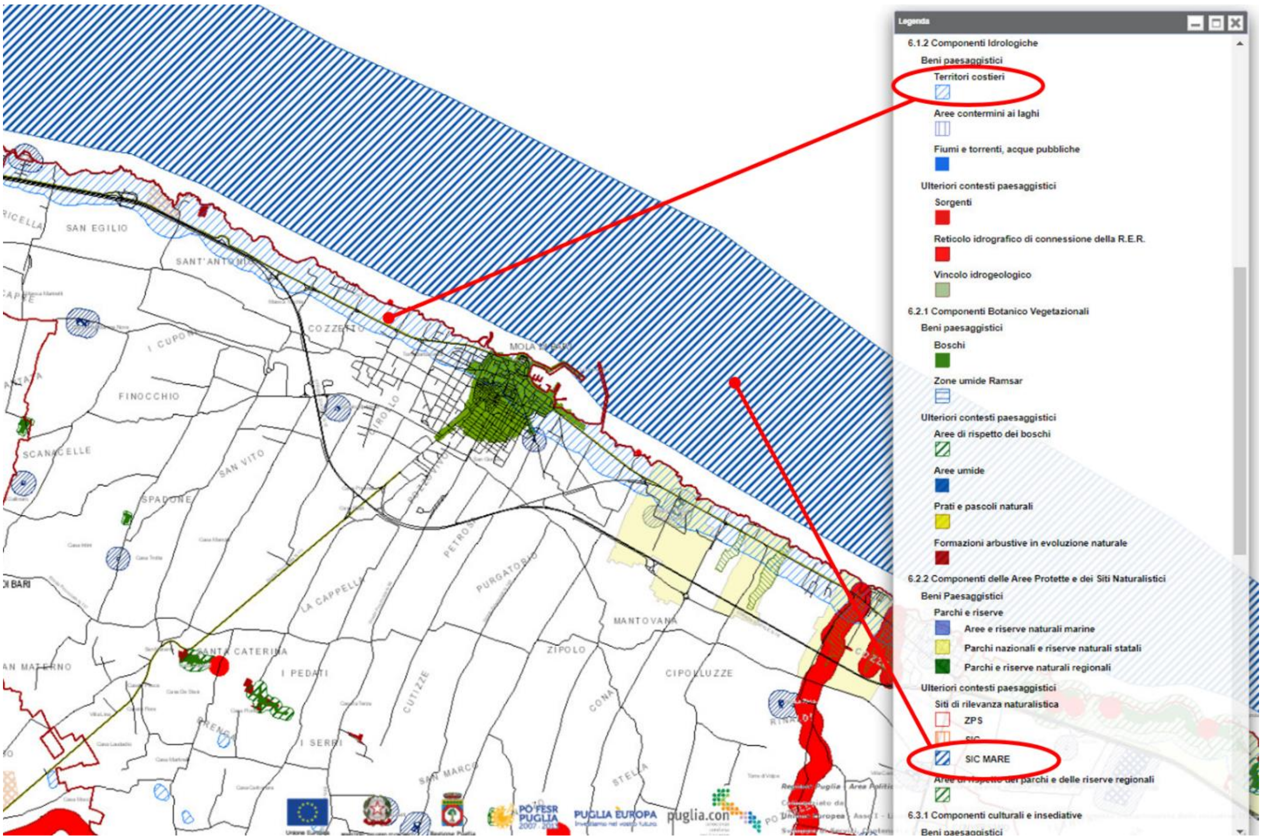

Figure 30. Landscape protection of coastal areas (300-m strip of land along marine coasts), and Natura 2000 site SAC IT9120009 – Posidonieto San Vito-Barletta (source: SIT Regione Puglia).

6 Other spatial constraints

The Tritone web portal run by RSE (a research company owned by GSE, the national grid operator) provides the spatial location of naval commercial routes and underwater infrastructure. The figure below shows that there is no interference between the above and the proposed location of the ISWEC devices. However, there could likely be a relevant interference with fishing activities and pleasure boating.

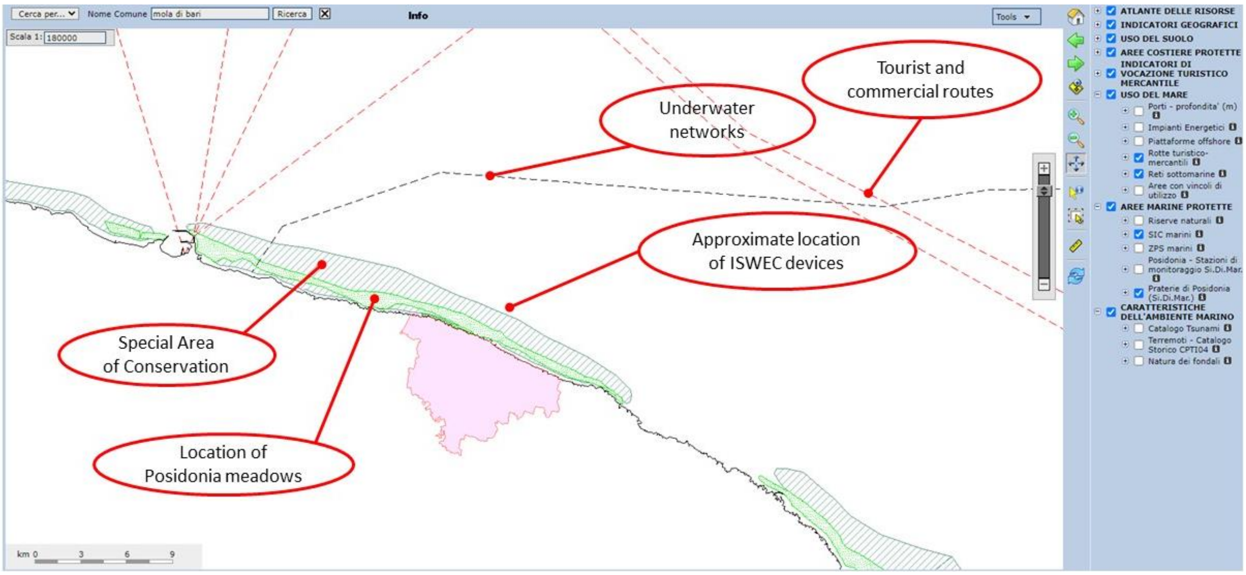

Figure 31. Identification of underwater networks and naval routes and approximate location of ISWEC devices (source: http://tritone.rse-web.it/).

7 Possible time schedule

A possible time schedule for the design and execution of works, including surveys and authorisation procedures, is illustrated in the chart below.

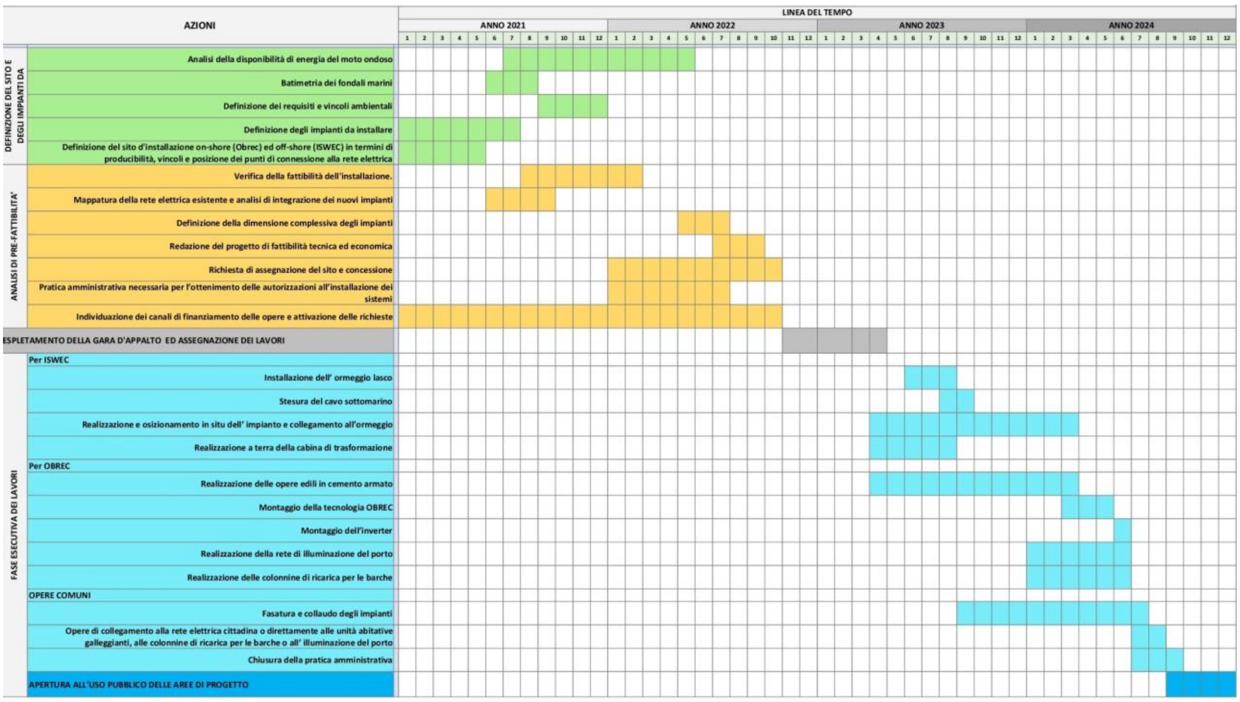

Figure 32. Possible time schedule for the installation of the ISWEC and OBREC systems.

8 SWOT analysis

8.1 ISWEC

Strengths	Weaknesses
- The device is being developed specifically for the low-power and low-height waves of the Mediterranean - The design of the device can be modified and adjusted to the local characteristics of the sea - The device allows for a certain degree of tuning to the varying sea conditions while in operation, thanks to the possibility of regulating the flywheel speed - The device has a very low visual impact - The device has a low impact on the seabed, since there is no permanent mooring, and the anchors are prevented from sliding thanks to a "virtual seabed" system of chain stretches, floaters and counterweights able to dissipate the hull's pulling energy - The device does not contain dangerous fluids and does not emit electromagnetic waves - Preliminary monitoring of parameters related to Posidonia meadows, hydrology, nutrients, and heavy metals in the Pantelleria test site have not shown evident impacts by the prototype - All the mechanical parts are protected by the hull and operate in a dry environment, therefore maintenance is reduced and lifetime is maximised - The maintenance operations are simple thanks to a direct access to the mechanical parts inside the hull - The device can be integrated with a PV system to be placed on the deck of the floater	- The anchoring system has a – albeit limited – interaction with the seabed, with possible consequences on sediments, flora and fauna; in particular, it is not suitable for sites with Posidonia meadows - The system needs to be connected to the mainland through an underwater cable, creating interactions with sediments, flora and fauna - The noise generated by the moving parts and the vibrations of the hull and anchoring system has been found to exceed the natural noise levels of the marine environment especially at lower frequencies, with possible impacts on fish life - The floating elements, the mooring system and the electric cable can cause interactions and conflicts with fishing activities and other uses of the sea - The system needs input energy to overcome bearing and air drag losses caused by the rotation of the flywheel - The device is still under development and the existing prototypes have been tested only in environments with wave conditions that are different from those of the pilot area - There is very little data available on the electricity production, costs and life span of the device - The optimal location and the optimal dimensions of the device must be studied based on detailed data from local, ad-hoc monitoring of wave conditions, which implies additional costs and time - The cost of deployment of a single device is quite high, considering also the costs for the electrical connection to the mainland - There is currently poor and contrasting information available on the costs of the prototypes; it is therefore difficult to make a feasibility assessment

Strengths	Weaknesses
	- Unless the manufacturing costs are not considerably reduced in the next development phases, this device will be probably suitable only for small islands or other places where the energy costs are higher; at the current state of development, the costs for building the device and connecting it to the mainland seem to be far from competitive

Opportunities	Threats
- The seabed in steeper in the pilot area compared to other sites along the Italian Adriatic coast, therefore the devices can be deployed at a relatively limited distance from the coast (2-3 km) - There is a higher wave height and power in the pilot region compared to the rest of the Adriatic Sea - The City of Mola di Bari is available in providing a further testing opportunity for a device having already been tested in different environments - This technology has recently raised the interest by ENI (energy company), Cassa Depositi e Prestiti (national institution financing investments by public authorities), Fincantieri (shipbuilding group), and Terna (national grid operator), which gives evidence of its potentials	- Generally speaking, there is low wave height and power in the Adriatic Sea, which makes it unsuitable to most off-shore WEC devices - There is a 2,000-m wide marine Natura 2000 site along the coast, which might imply a request to make an Appropriate Assessment for obtaining an authorisation for the mooring system and the electrical cable connection - There is poor data available on wave height, period and power densiy in the pilot area, therefore it is difficult to obtain an accurate pre-estimate of the possible energy outputs of the device before an ad-hoc monitoring campaign - The system operation could be prone to scheduled interruptions to avoid acoustic impacts on fish life in certain periods of the year, causing lower energy yields - Given its relatively low degree of TRL and limited potential of electricity production, the deployment of this type of device is less likely to receive funding compared to more mature and productive technologies (e.g. off-shore wind)

8.2 OBREC

Strengths	Weaknesses
- The device can be integrated in existing breakwater/piers, e.g. by substituting the traditional rubble mounds with the OBREC	- The device is still under development and the existing prototypes have been tested only in

Strengths	Weaknesses
caissons; it can also be built in newly constructed piers - The device, if integrated into a breakwater, does not cause conflicts with other uses of the sea - A breakwater equipped with OBREC can even improve its hydraulic performances in terms of reduced overflow and reflection coefficient - The device has a very low visual impact, comparable to that of a traditional breakwater/pier - A breakwater structure shaped specifically to host an OBREC device (i.e. concrete ramp, reservoir and caisson replacing the traditional rubble mound) is cheaper than a traditional breakwater and has similar – if not better – hydraulic perfomances if specific design conditions are met; therefore, building a new breakwater with this shape can in any case be a no-regret solution providing additional benefits, independently from its energy productivity - The device has apparently low on-site environmental impacts, even if specific studies are yet to be made - The City of Mola di Bari is available in providing a further testing opportunity for a device having already been tested in different environments	environments with wave conditions that are different from those of the pilot area - The wave power along the Apulian coast is lower than at the test site in the port of Naples, and this prevents from making precise estimates on the possible output of the device - The dimensions of the structure should be carefully adapted to the local wave climate; this does not allow to have a standard, one-fits-all model, and makes costs of each installation higher - The device contains parts that are submerged (turbines) or in contact with marine water, therefore being subject to corrosion and needing constant maintenance - According to the currently available information, the installation of an OBREC device would approach a reasonable payback time only if sharing the costs for the construction of a new pier; conversely, it would not be economically feasible if installed on an existing pier - The device could have impacts on fishes and other animals that might get caught in the reservoirs; no study is currently available on this aspect - The device could have acoustic impacts; no study is currently available on this aspect - There is scarce information about the possible costs of a fully operating OBREC device; it is therefore difficult to make a feasibility assessment

Opportunities	Threats
- There is a higher wave height and power in the pilot region compared to the rest of the Adriatic Sea - There is no particular landscape nor environmental restriction on the port area	- Generally speaking, there is low wave height and power in the Adriatic Sea - There is poor data available on wave power in the pilot area, therefore it is difficult to obtain an accurate estimate of the possible energy outputs of the device - Currently, there is no very low-head turbine for sea applications available on the market, and the tests in Naples are being made with turbines that are not totally fit for this application; therefore, there is still no reliable data on the productivity of the system

Opportunities	Threats
	- Given its relatively low degree of TRL and limited potential of electricity production, the deployment of this type of device is less likely to receive funding compared to more mature and productive technologies (e.g. off-shore wind)

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9.2 Web resources

1. ARERA's webpage on the trend of electricity prices: https://www.arera.it/it/dati/eep35.htm
2. ENI's webpage about ISWEC: https://www.eni.com/it-IT/attivita/onde-mare-energia.html

3. Geoportale nazionale: http://www.pcn.minambiente.it/
4. ISPRA's wave measuring network: https://www.mareografico.it/?session=0S3562038343EYDT79U8666&syslng=ita&sysmen=-1&sysind=-1&syssub=-1&sysfnt=0&code=RETE&idr=4
5. Maestrale+Coastenergy webGIS: http://192.167.120.31/lizmap-web-client-3.1.4/lizmap/www/index.php/view/map/?repository=maestrale&project=maestrale
6. Navionics chart viewer: https://webapp.navionics.com/?lang=it#boating@6&key=_vt~FwzjkA
7. https://www.waveforenergy.com/
8. Presentation of the deployment of the ISWEC prototype at the Pantelleria test site: https://www.youtube.com/watch?v=01tGBVGMYQQ&ab_channel=PlayUniud
9. Tritone RSE portal: http://tritone.rse-web.it/
10. WebGIS of the Regional Landscape Plan of Apulia: http://webapps.sit.puglia.it/freewebapps/PPTRApprovato/index.html