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# Wave Energy Converters: A State-of-the-Art Review of Wave-Activated Body Technologies

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**Abstract**

Wave energy is a renewable resource with enormous, untapped potential. Devices known as WABs (Wave-Activated Bodies) constitute the most diverse category of WECs (Wave Energy Converters). This review systematically analyzes the state of the art in WAB technology development, evaluating their Technology Readiness Level (TRL), energy performance, mass-to-power ratio, economic indicators (LCOE and CAPEX), and potential applications, with specific attention to the Mediterranean basin. To focus on technologies with realistic near-term deployment prospects, the analysis is deliberately restricted to devices with a maturity of at least TRL 5 (TRL $\geq$ 5); on this basis, ten devices spanning four representative subcategories (point absorbers, attenuators, flexible tube devices and gyroscopic systems) were examined. Point absorbers are the most mature and best-represented class: compact resonant converters such as CorPower Ocean C4 have been tested and grid-connected in open ocean conditions, achieving among the most favorable mass-to-power ratios (about 200 t/MW). The Mocean Blue X attenuator and the SBM S3 flexible tube converter illustrate alternative, storm-resilient architectures at intermediate maturity, the latter replacing rigid hulls and conventional power take-offs with an elastomeric tube and distributed electroactive conversion. Gyroscopic systems enclose all moving parts within a sealed hull; among them, ISWEC is the only WAB device grid-connected in the Mediterranean Sea. Across all classes, the mass-to-power ratio emerges as the key driver of economic competitiveness, while integrated WEC–PTO–control co-design is the main lever for reducing the LCOE. Device-level cost data are rarely disclosed at pre-commercial stages, so the comparison is reported as an evidence-bounded ranking that distinguishes demonstrated performance from undisclosed information, together with the most realistic routes toward bankable Mediterranean wave farms.

**Keywords:** Wave Energy Converter; Wave-Activated Body; Mediterranean Sea; TRL assessment; Power Take-Off; marine renewable energy

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## 1. Introduction

The global energy transition toward renewable sources represents one of the most daunting challenges of the 21st century. Among the resources not yet fully exploited, wave energy offers, according to Mørk et al. [1], an estimated global theoretical potential of 3.0–3.7 TW, equivalent to approximately 26,000–32,000 TWh/year. This amount of energy is of the same order of magnitude as current global electricity demand (32,132 TWh in 2025), although it represents a purely theoretical estimate of the available resource.

Compared to other renewable sources, wave energy offers significant advantages, including high energy density (among the highest among renewable sources), good predictability of average available power, and resource availability of up to 90% of the time [2]. Devices for converting wave energy into electricity, known as Wave Energy Converters (WECs), have been the subject of intense research and development over the past few decades. The classification of these technologies varies widely in the literature based, for example, on the operating principle, orientation, and installation location.

Falcão [3] proposes an academic classification based on hydrodynamic principles, distinguishing three main categories: Oscillating Water Column (OWC), Oscillating Body Systems (also known as Wave-Activated Bodies, WABs), and Overtopping devices. The European Marine Energy Center (EMEC) [4], on the other hand, adopts a more detailed industrial classification, identifying eight types: Point Absorber, Attenuator, Oscillating Wave Surge Converter (OWSC), Submerged Pressure Differential, Oscillating Water Column (OWC), Overtopping, Bulge Wave, and Rotating Mass.

In WAB devices, ocean waves interact directly with the WEC, producing movements in floating or submerged components. In turn, the resulting motion is converted by the Power Take-Off (PTO) into the desired form of energy. These systems constitute the most varied category. These devices can operate with varying degrees of freedom (heave, surge, pitch, sway, roll, yaw) and include diverse subcategories based on operating principle, power scale, and application context [3]. The variety of approaches reflects the intrinsic complexity of the wave resource and the wide range of operating conditions under which WECs must function.

Despite decades of development, the wave energy sector has not yet reached commercial maturity. The Levelized Cost of Energy (LCOE) remains significantly higher than that of other renewables: while offshore wind has reached values of 50–80 €/MWh, wave energy costs remain several times higher and strongly site-dependent [5], with published techno-economic estimates placing WEC LCOE at roughly 300–1200 €/MWh (see Section 3.5). The main barriers include reliability in a hostile marine environment, offshore installation and maintenance costs, and the need to ensure structural integrity during storm conditions [6]. However, recent technological advances have enabled several devices to reach Technology Readiness Levels (TRL) of 7–8, with full-scale demonstrations and grid connection [7].

Most studies and pilot installations focus on sites with high energy potential, such as the European Atlantic coast, the North Sea, and the coasts of Australia and the United States. The Mediterranean Sea, characterized by a less energetic but more regular wave regime (the most productive areas do not exceed 12 kW/m of annual average wave energy flux), has received less attention despite offering specific opportunities, such as powering remote islands and integrating with other marine renewables [8]. Milder weather and sea conditions could also favor more compact and lightweight devices, with potential advantages in terms of capital costs, maintenance, and device survival.

This study aims to provide a systematic review of the state of the art in emerging WAB technologies. The specific objectives are:

- to compare the performance of the different WAB subcategories in terms of TRL and techno-economic indicators;
- to identify the critical parameters for economic competitiveness, with particular attention to the mass-to-power ratio;
- to assess the applicability of the different technologies in Mediterranean contexts.

Several previous reviews have addressed wave energy conversion technologies, typically offering broad technological overviews or focusing on a single WEC category (e.g., point absorbers or oscillating water columns) and relying on narrative rather than quantitative comparison. Relative to this body of work, the present review makes three

specific contributions: (i) a systematic, evidence-based multi-criteria assessment that scores each device against four performance criteria (Section 2.5), rather than a purely descriptive comparison; (ii) a restriction of the analysis to WAB technologies with a minimum Technology Readiness Level of 5, so that the devices discussed are grounded in demonstrated rather than purely conceptual performance; and (iii) an explicit evaluation of the suitability of each technology for the Mediterranean wave climate, a context that has received comparatively little attention in the WEC review literature relative to the higher-energy Atlantic and North Sea settings.

## 2. Methods

### *2.1. Systematic Literature Search Strategy*

This study was conducted through a systematic review of scientific and technical literature; the papers and articles examined were published between 2009 and 2025. The databases consulted included Scopus, Web of Science, ScienceDirect, and Google Scholar. The search strings used included combinations of the following terms: "wave energy converter," "wave-activated body," "point absorber," "gyroscope systems," "flexible tube devices," "wave power," "marine renewable energy," "ocean energy," and "TRL" or "technology readiness level."

Non-academic technical sources relevant to the sector were also consulted, including reports from the International Energy Agency–Ocean Energy Systems (IEA–OES) [7]; technical documentation from the European Marine Energy Center (EMEC) [4]; the PRIMRE (Pacific Region Integrated Marine Renewable Energy) project database; official websites of WEC technology manufacturers and developers; and proceedings from international conferences (EWTEC, OMAE, ICOE).

### *2.2. Selection Criteria*

The devices included in the review were selected according to the following criteria:

- **Temporal criterion**: active development or documented testing during the 2015–2025 period;
- **Technological criterion**: classification as a Wave-Activated Body according to Falcão's classification [3] or related categories in the EMEC taxonomy [4];
- **Maturity criterion**: Technology Readiness Level of at least 5 (TRL $\geq$ 5), i.e., a device whose components or full system have been validated through sea or basin trials in a relevant environment, rather than at the proof-of-concept stage only;
- **Data availability criterion:** presence of publicly accessible technical information on rated power, dimensions or operating principles.

Purely conceptual and early laboratory devices (TRL < 5), technologies abandoned before 2015 without subsequent development, and pure overtopping devices not falling within the definition of WAB were excluded. The TRL $\geq$ 5 threshold was adopted deliberately: it keeps the review focused on technologies with realistic near-term deployment prospects and, at the same time, keeps the manuscript within a manageable length by excluding the large number of early-stage concepts that would not add to the technology-readiness and techno-economic assessment that is the aim of this work.

The review followed a PRISMA-style workflow comprising four stages. In the identification stage, the search strings of Section 2.1 were run on the four databases and complemented by the gray literature sources listed above. In the screening stage, records were filtered by title and abstract to remove duplicates and clearly out-of-scope items (tidal, OTEC, pure oscillating water column and overtopping devices, and studies below TRL 5). In the eligibility stage, the remaining full texts and technical datasheets were assessed against the temporal, technological, maturity (TRL $\geq$ 5), and data availability criteria de-

fined above. In the inclusion stage, only the devices satisfying all criteria were retained, yielding the ten WAB devices analyzed in Section 3 across the four most representative subcategories. The same workflow was applied to the dedicated literature on PTO systems summarized in Section 4.

### 2.3. Classification System

In the literature, eleven main subcategories of wave energy converters can be distinguished, based on their primary operating principle:

1. **Point Absorbers**: devices are characterized by horizontal dimensions smaller than the wavelength and exploit mainly the heaving motion.
2. **Attenuators**: these elongated structures are oriented parallel to the direction of wave propagation.
3. **Oscillating Water Columns** (OWC): these systems are based on the compression/decompression of air inside a partially submerged chamber, due to the alternative motion of waves.
4. **Oscillating Wave Surge Converters** (OWSC): devices exploit the horizontal movement of water particles, mainly in nearshore areas.
5. **Submerged Differential Pressure Devices**: WECs operate completely submerged, exploiting the alternating variation in the hydrostatic pressure.
6. **Gyroscopic Systems**: devices are based on the induced precession of gyroscopic flywheels due to wave motion.
7. **Flexible Tube Devices**: these attenuators consist of elastic tubes that exploit internal pressure waves to activate a hydroturbine.
8. **Biomimetic Systems**: these systems are designed with peculiar shapes and materials, inspired by marine organisms.
9. **Nanogenerators**: micro-power devices based on the triboelectric or piezoelectric effect.
10. **Hybrid Systems**: these platforms integrate wave energy with other renewable sources (solar, wind).
11. **Other Devices**: emerging technologies not classifiable in the preceding categories.

For the purposes of this review, ten devices belonging to the four most representative WAB categories were identified, i.e., categories 1, 2, 6 and 7. Figure 1 summarizes the classification of wave energy technologies adopted in this review and the position of the four WAB subcategories analyzed in the following sections.

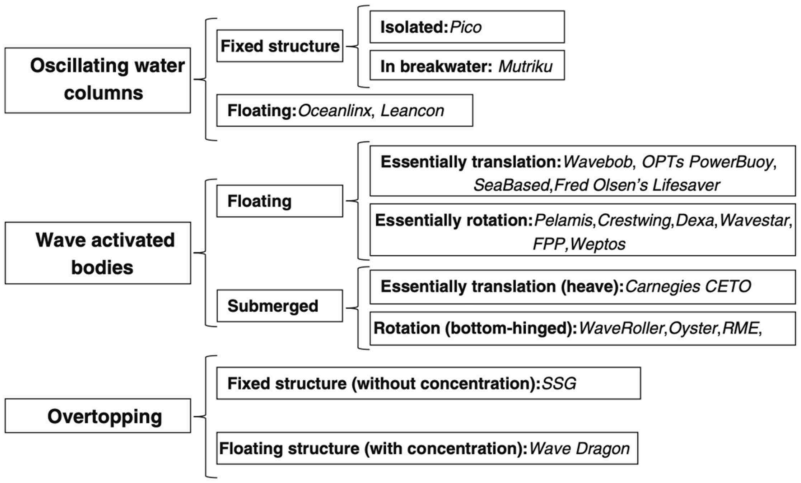



**Figure 1.** Categorization of wave energy technologies following IEA–Ocean Energy Systems. Technologies mentioned in the various categories are those illustrated in the following sections (Ocean Energy Systems) [9].

### 2.4. Analyzed Parameters

For each device in every subcategory, technical specifications were collected and analyzed, where available from datasheets, papers, webpages, reports, etc. In particular:

- Main characteristics: rated power (kW or MW), characteristic dimensions (length, diameter, height), total mass (t), operating depth (m), and mooring system;
- Energy conversion: mass-to-power ratio (t/MW), capture width ratio, PTO, storage, output;
- Development status: Technology Readiness Level (TRL) according to the 1–9 scale adopted by Horizon Europe [10], year of deployment, test site;
- Economic indicators, where publicly disclosed: LCOE (€/MWh or $/MWh), CAPEX (€/kW). These figures are rarely released by developers at pre-commercial stages and are reported as "not publicly disclosed" where unavailable (see discussion in Sections 3.5 and 5);
- Survivability characteristics, where documented in the source material: maximum wave height survived, operational lifespan, protection strategies (detuning, submersion, variable geometry).

### 2.5. Quantitative Synthesis and Device Scoring

To move beyond a purely descriptive catalog, the collected data were synthesized quantitatively through a transparent multi-criteria scoring scheme. Each device was rated on a 1–5 scale against four performance criteria: technological maturity, derived from the assessed TRL; mass-to-power ratio, used as a proxy for capital intensity; demonstrated survivability, based on documented storm survival or an explicit storm protection strategy; and Mediterranean suitability, based on omnidirectional capture, compactness and the exploitation of wave slope rather than absolute wave height. The criteria were given equal weight, and the resulting scores fed the comparative assessment presented in Section 3.5.

A deliberate distinction was drawn between demonstrated poor performance and absence of public evidence. A score of 1 was assigned only where the source material documented a value falling in the lowest band; where no public evidence could be retrieved for a criterion, the criterion was recorded as n.d. (not disclosed) and was excluded from the score rather than assigned the lowest value. Treating undisclosed information as equivalent to demonstrated underperformance would penalize developers on the basis of a disclosure behavior that is unrelated to the technical merit of the converter. Because excluding a criterion is itself an assumption, each device is characterized not by a single total but by its evidence coverage (k out of 4) and by a score range, bounded below by assigning the minimum value to every n.d. criterion and above by assigning the maximum. The width of the range therefore measures how much of a device's position rests on evidence and how much on missing information, and devices whose ranges overlap are not considered separable on the available evidence.

Techno-economic evidence is deliberately not included as a scored criterion. Device-level LCOE and CAPEX figures are almost never released at pre-commercial stages (Section 3.5), so a criterion built on their availability would measure the disclosure practices of developers rather than the cost competitiveness of the technology, and would propagate that bias into the ranking. The availability and provenance of techno-economic evidence are instead reported alongside the scores as a separate qualitative descriptor, so that readers can judge the strength of the cost evidence for each device independently and re-weight the criteria according to their own priorities.

## 3. Comparison Results on WAB Technologies

This section describes in detail some devices belonging to the categories mentioned above. In Section 3.5, a comparison of the various devices is reported.

### *3.1. Point Absorber*

In the analysis of technologies related to point source absorbers, technical correlations were performed on the following devices:

- CorPower Ocean C4;
- CorPower Ocean C5;
- OPT PowerBuoy;
- Carnegie CETO 5;
- Carnegie CETO 6;
- Nankun China Southern Power Grid;
- Lysekil Project.

#### 3.1.1. CorPower Ocean C4

The CorPower Ocean C4 is a point source wave energy converter developed by the Swedish company CorPower Ocean, whose design is inspired by the pumping action of the human heart, as conceived by cardiologist Stig Lundbäck. The device was installed in August 2023 at the Aguçadoura test site, approximately 4 km off the Portuguese coast, moored at a depth of 45 m using the innovative "UMACK" anchoring system and connected to the national power grid via an undersea cable. The C4 consists of a float that oscillates vertically with the passage of waves. The distinctive feature of the technology is the WaveSpring system, which enables active tuning of the device: under normal operating conditions, the mechanism amplifies the float's movement by resonating with the incident wave, while during extreme events the system is "detuned" to reduce structural loads. The vertical linear motion is converted into rotation via a high-efficiency cascade gearbox, protected by a pneumatic pre-tensioning system that limits the overall weight [11].

During the commissioning phase (September–October 2023), the C4 reached power peaks of up to 600 kW. Subsequent improvements to the electrical system and inverters brought the peak power capacity from the verified 600 kW toward 850 kW. The device demonstrated excellent survivability, successfully withstanding Storm Domingos (November 2023) with maximum wave heights of 18.5 m. In detuned mode, the internal motion of the mechanism is limited to a few decimeters, drastically reducing structural stress [11]. Figure 2 shows the C4 converter, while Tables 1 and 2 report the main specifications of the device and the anchor, respectively.

The main characteristics of the Umack anchor are listed in Table 2.

#### 3.1.2. CorPower Ocean C5

The CorPower Ocean C5 represents the commercial evolution of the technology developed by CorPower Ocean and is designed to achieve a rated power of 1.5 MW, five times that of its predecessor, the C4. The device is intended for installation in a pilot array called "Tethys" [11], consisting of three units, with a demonstration phase scheduled for 2026–2027. The C5 retains the same operating principle as the C4, based on WaveSpring technology and advanced phase control. The system operates in three basic modes:

- Amplified resonance: Using pneumatic springs and actuators, the device tunes into the incident wave, oscillating in perfect resonance. This amplification allows it to capture significantly more energy than traditional devices of the same size.
- Internal conversion: The amplified vertical linear motion is converted into electrical energy via a mechanical transmission system and an integrated generator.

- Storm resistance: Under extreme weather and sea conditions, the system is capable of detuning or blocking resonance, thereby protecting the structure and allowing the wave to pass with reduced mechanical stress.

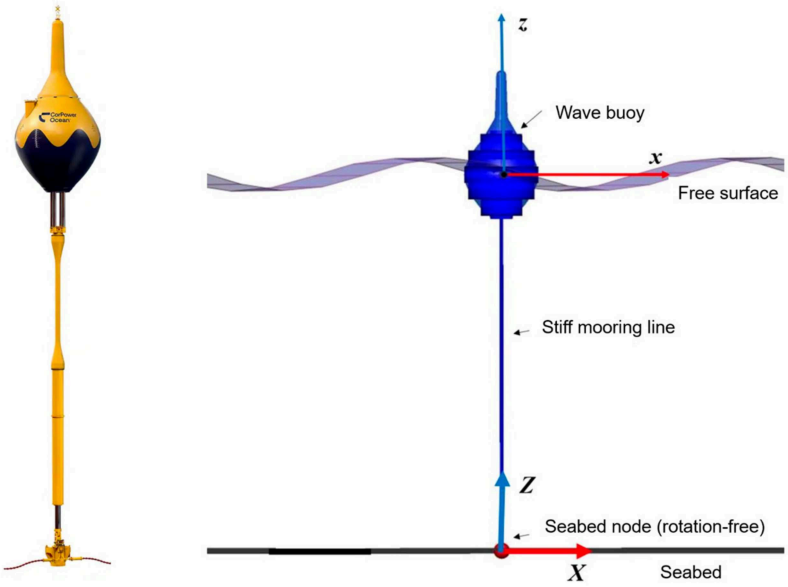



**Figure 2.** CorPowerOcean C4 prototype and the numerical model [12].

**Table 1.** General specifications of the CorPowerOcean C4.

| Parameter | CorPower Ocean C4 |
|---|---|
| Rated power | 300 kW (peak 600 kW) |
| Installation depth | 45 m |
| TRL | 7 |
| Mass | 60 t |
| Mass to power ratio | ~200 t/MW |
| Operating distance from shore | ~ 4 km offshore |
| Survival wave height | 18.5 m (storm Domingos, November 2023) |
| Survival mode | Detuning |
| Test | Sep–Oct 2023 (+ongoing) |
| Technology | Wave spring with active tuner (resonance/detuning) |
| Inspiration/origin | Cardiac pumping principle |
| Target sector | Renewable energy |
| Advantages | Excellent mass to power ratio<br>Survivability (18.5 m demonstrated)<br>Active tuning |
| Disadvantages | Capex costs not available |

**Table 2.** Technical specifications of the Umack anchor connected to the CorPowerOcean C4 device.

| Umack Anchor | Data |
|---|---|
| Diameter | 1.6 m |
| Length | 24 m |
| Mass | 43 t |
| Maximum tensile capacity | 15,000,000 N |

CorPower Ocean's stated goal is to overcome the two long-standing barriers to wave energy: efficiency/cost and reliability. By amplifying wave motion, the device generates more energy per ton of equipment, making it more compact, lighter, and consequently cheaper to manufacture, transport, and install. The goal is to achieve an LCOE competitive with offshore wind power. The C5 represents the final phase of the "HiWave-5" project, which aims for bankable certification of the technology and the demonstration of a pilot array connected to the Portuguese power grid; specifically, the project will include one C4 WEC and three C5 WECs for a total of 4.8 MW. Table 3 summarizes the main specifications of the C5.

**Table 3.** General specifications of the CorPowerOcean C5.

| Parameter | CorPower C5 |
|---|---|
| Rated power | 1.5 MW |
| Array configuration | 3 units (Tethys) |
| TRL | 5–6 |
| PTO | WaveSpring + phase control |

#### 3.1.3. PowerBuoy 2.0

The Next-Generation PowerBuoy, also known as PowerBuoy 2.0, is a device developed by Ocean Power Technologies (USA) that stands out as a multi-energy hybrid platform. Unlike traditional WECs focused exclusively on wave energy conversion, the PowerBuoy 2.0 integrates three renewable energy sources into a single floating structure: wave energy, solar energy, and wind energy [13]. The device consists of a buoy approximately 14.5 m tall with a draft of 8.7 m and a spar diameter of 1.3 m. The total weight ranges between 13 and 16 tons depending on the installed payload. Wave energy is converted through the structure's vertical movement: as the outer part of the buoy rises and falls with the wave, an internal mechanism converts this movement into electricity. To complete the energy system, the PowerBuoy 2.0 is equipped with solar panels (4.1 kW capacity) and two small wind turbines [13]. The energy produced is stored in a high-capacity battery system (44–88 kWh), ensuring continuous and reliable power to onboard equipment or connected underwater devices. The standard electrical interface operates at 24 Vdc with the option for top and underwater umbilical connections. The main innovation of the PowerBuoy 2.0 lies in its function as a multi-mission platform. The device effectively serves as a hub for real-time data collection and communications, with LTE/4G/5G and satellite connectivity. Key applications include offshore energy supply and monitoring for the oil, gas, and offshore wind industries, and scientific research, where the system enables remote sensor powering and environmental data collection over extended periods. The mooring system is designed to withstand extreme conditions, with certification for North Sea storms with a 50-year return period. Available configurations include single-point mooring with a lateral bridle, three-point mooring with umbilical and auxiliary buoys, or combined umbilical mooring. The seabed interface can utilize traditional anchors or gravity bases [13]. In September 2024, OPT completed long-term testing of the device, confirming its operational performance under real-world conditions. Figure 3 below illustrates the PowerBuoy 2.0, and Table 4 lists its main specifications.

**Table 4.** General specifications of the PowerBuoy 2.0.

| Parameter | PowerBuoy 2.0 |
|---|---|
| Device type | Hybrid point absorber (wave + solar + wind) |
| Height | 14.5 m |
| Draft | 8.7 m |

**Table 4.** *Cont.*

| Parameter | PowerBuoy 2.0 |
|---|---|
| Spar diameter | 1.3 m |
| Mass | 13–16 t |
| Solar capacity | 4.1 kW |
| Wind generation | 2 turbines |
| Nominal ESS capacity (batteries) | 44–88 kWh |
| TRL | 7 |
| Status | Operational |

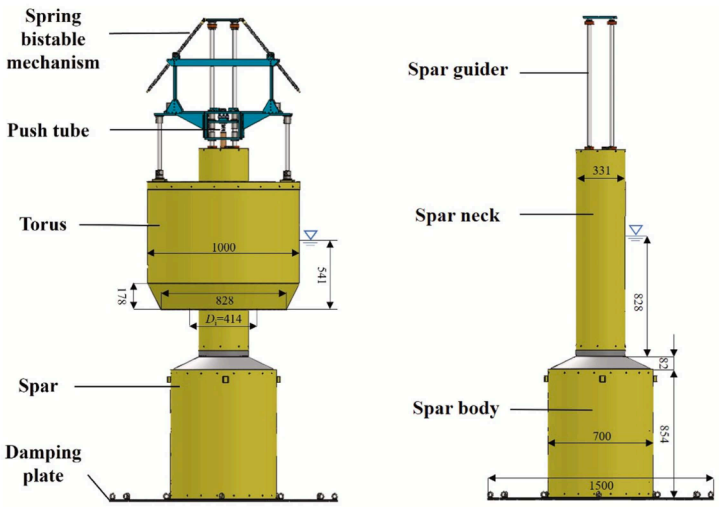



**Figure 3.** PowerBuoy 2.0 [14].

#### 3.1.4. Carnegie CETO 5

The CETO 5 is a wave energy converter developed by Carnegie Clean Energy (Australia), representing a milestone in the development of submerged technology for harnessing wave energy. The name "CETO" derives from the Greek god of the sea, and the device is notable for being one of the world's first commercial plants to generate energy from waves in a fully submerged configuration [15]. The system was demonstrated in the Perth Wave Energy Project (PWEP), off the west coast of Australia near Garden Island. CETO 5 consists of a series of submerged buoys, each with a diameter of approximately 11 m and a rated power of 240 kW, positioned just below the water's surface. This configuration ensures invisibility from the shore and protection from the most violent waves and storms [15]. The operating principle is based on a three-stage hydraulic system:

- Motion capture: CETO buoys, driven/carried by wave motion, move vertically like pistons (in reality, this is a three-dimensional orbital motion, so not strictly vertical);
- Water pumping: The motion drives hydraulic pumps that force seawater at high pressure through an underwater pipeline;
- Onshore generation: High-pressure water flows to a coastal hydroelectric power plant, where it drives a conventional turbine to generate electricity.

A distinctive feature of the CETO 5 is its ability to simultaneously generate electricity and produce fresh water. The high-pressure water system can supply a reverse osmosis desalination plant, enabling the production of drinking water with zero emissions. This capability was particularly important for supplying the HMAS Stirling naval base, to which the plant was connected [16].

The CETO 5 project operated successfully for over a year, setting industry records for operating hours and demonstrating the commercial viability of the submerged technology.

The lessons learned were subsequently applied in the development of CETO 6, which integrated the generators directly within the buoys, eliminating the need to pump high-pressure water ashore [15]. The main technical specifications are shown in Table 5. The CETO 5 system is shown in Figure 4.

**Table 5.** General specifications of the CETO 5.

| Parameter | CETO 5 |
|---|---|
| Device type | Submerged point absorber |
| Rated power (per unit) | 240 kW |
| Buoy diameter | 11 m |
| Operating depth | Sub-surface |
| PTO | Hydraulic (high-pressure water pumping) |
| Additional functionality | Desalination |
| TRL | 7 |
| Status | Completed |

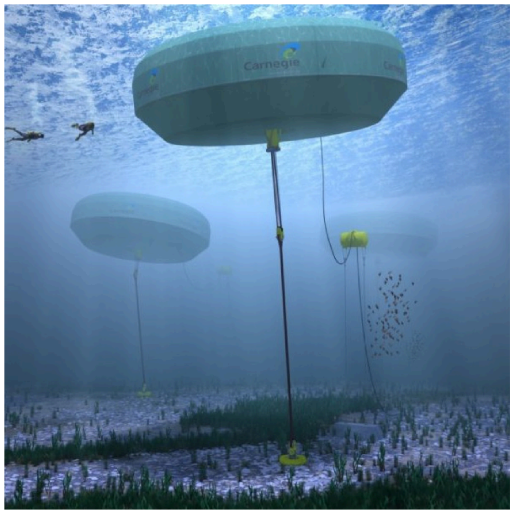


**Figure 4.** Carnegie CETO 5 [17].

3.1.5. Carnegie CETO 6

CETO 6 represents the technological evolution of CETO 5, developed by Carnegie Clean Energy with the aim of significantly reducing costs and increasing rated power, transforming the engineering concept into a market-ready solution. The main innovation lies in the integration of electricity generation directly on board the submerged buoy [18]. In the CETO 5, energy was transferred to shore in the form of high-pressure water, requiring a complex system of underwater pipelines. In the CETO 6, however, the electric generators are installed inside the buoy itself, producing electricity on-site. This modification is crucial for cost reduction and scalability: it is no longer necessary to install and maintain expensive high-pressure pipelines stretching for kilometers along the seabed. The electricity generated underwater is transmitted to shore via a standard submarine power cable [18]. The main features of CETO 6 include:

- Increased power: a rated capacity of 1.5 MW per unit, approximately six times greater than the 240 kW of the CETO 5, which is essential for making wave energy economically competitive;
- Fully submerged configuration: like its predecessor, the device is completely submerged and anchored to the seabed, ensuring protection from storms, zero visual impact, and minimal environmental impact on marine life;

- Easy installation and maintenance: the design has been optimized to reduce the need for expensive heavy-lift vessels, simplifying operations and lowering associated costs;
- Microgrid integration: the CETO 6 is designed to integrate with other renewable energy sources (solar) and energy storage systems, creating autonomous and resilient microgrids that are ideal for islands or remote bases [19].

The CETO 6 was the centerpiece of the Albany Wave Energy Project (AWEP) in Australia, a project aimed at testing and demonstrating the 1.5 MW commercial-scale unit and bringing the technology to a bankable level of maturity (the project was canceled in March 2019; for this reason, its TRL is lower than that of the CETO 5, as it was never demonstrated in a real-world operational environment). Table 6 reports the main specifications of CETO 6.

**Table 6.** General specifications of the CETO 6 device.

| Parameter | CETO 6 |
|---|---|
| Device type | Submerged point absorber |
| Rated power | 1.5 MW |
| PTO | Onboard integrated electric generators |
| Operating depth | Sub-surface |
| Power transmission | Submarine power cable |
| Target | Grid-scale, microgrid, remote islands |
| TRL | 5–6 |
| Status | Under development |

Carnegie has also initiated international collaborations, including an agreement with Enel Green Power to develop projects in Europe, with potential deployment in Spain planned for the 2024–2025 period [20]. The CETO 6 safety system includes automatic protection mechanisms that allow the buoy to adapt to extreme marine conditions, maintaining structural integrity even during severe weather events.

#### 3.1.6. Nankun (China Southern Power Grid Nankun)

The Nankun represents a significant milestone in China's marine energy sector, as it is the first megawatt-scale wave energy converter developed independently by China. The device was launched on 15 June 2023, off the coast of Zhuhai, in Guangdong Province [21]. Unlike compact point absorbers such as the CorPower C4, the Nankun takes a radically different approach: a large, semi-submersible floating platform with a triangular configuration. Its dimensions are impressive: 300 m long, 88 m wide, weighing 6000 tons, and with a displacement of 15,000 tons. The platform is equipped with 15 floating plates (five on each side) that capture wave energy [21]. Figure 5 shows the Nankun platform from different angles, and Table 7 summarizes its main specifications [22,23].

The conversion system operates through a three-stage process:

- Mechanical motion: the waves cause the floating plates to move vertically.
- Hydraulic conversion: hydraulic cylinders convert mechanical motion into hydraulic pressure.
- Electricity generation: the hydropower turbine drives the electric generators.

With a rated capacity of 1 MW, the plant can theoretically generate 24,000 kWh per day, enough to power approximately 3500 households. In actual operation, production averages around 10,000 kWh per day. The stated overall efficiency is 22%, with integrated solar panels for supplementary generation [21].

The Nankun plant is the result of decades of systematic development undertaken by China since the 1970s. Technological progress has been gradual; in fact, improvements can be observed over the years, particularly:

- 1990s–2000: first 10–20 kW systems;
- 2015: Sharp Eagle Wanshan 100 kW;
- 2019: 120 kW Penghu platform for aquaculture;
- 2020: 500 kW Zhoushan;
- 2023: 1 MW Nankun.



(**a**) (**b**)

**Figure 5.** Both figures (**a**,**b**) show photographs from different angles of the 1-megawatt Chinese platform named "Nankun," located off the coast of Zhuhai in Guangdong Province [24].

**Table 7.** General specifications of the Nankun.

| Parameter | Nankun |
|---|---|
| Device type | Point absorber * |
| Rated power | 1 MW |
| Length | 300 m |
| Width | 88 m |
| Mass | 6000 t |
| Displacement | 15,000 t |
| Mass to power ratio | ~6000 t/MW |
| Number of floating plates | 15 (5 per side) |
| Efficiency | 22% |
| Theoretical daily output | 24,000 kWh |
| Actual daily output | ~10,000 kWh |
| TRL | 6 |
| Status | Tested in 2023 |

* In detail, the device can exploit waves from many directions like a point absorber, despite its relevant dimensions in comparison to the wavelength.

A comparison with global leaders reveals substantial differences in design approach. While CorPower C4 achieves a mass-to-power ratio of approximately 200 t/MW (60 t per 300 kW), the Nankun has a ratio of approximately 6000 t/MW, which is significantly less favorable. This reflects two opposing design philosophies: a compact, high-efficiency single buoy versus a robust multi-absorber platform [21].

The main challenges for Nankun remain its high cost (estimated LCOE exceeding $44/MWh compared to competitors like Eco Wave Power), the unfavorable mass-to-power ratio, and the need to demonstrate long-term reliability. However, China's focus on niche applications—remote islands, offshore aquaculture, desalination—where wave energy is already competitive with expensive diesel, offers realistic paths to commercialization [21]. The device is currently undergoing testing in the South China Sea. The national goal is to reach 400 MW of installed offshore capacity by 2030, a 33-fold increase from 2023 levels.

#### 3.1.7. Lysekil Project

The Lysekil Project, led by the Division of Electricity at Uppsala University, has been operational at sea since 2006 [25,26]. The test site lies about 2 km offshore near Lysekil on the Swedish west coast (~100 km north of Gothenburg), on a 24–25 m sandy silt seabed covering roughly 40,000 $m^2$. It was chosen not for its modest wave resource (3.4 kW/m average in 2007) but for its proximity to marine research infrastructure and the ease of underwater inspection afforded by the shallow depth [25].

The Uppsala concept uses a permanent magnet (Nd-Fe-B) synchronous linear generator placed on the seabed and driven directly by a surface point absorber through a rigid connection. Eliminating any intermediate mechanical or hydraulic stage yields a mechanically simple, robust system, at the cost of a more complex electrical side, since the output voltage varies in both amplitude and frequency [25]. The first prototype—10 kW at 200 V, with a translator speed of 0.67 m/s—was deployed in March 2006 and linked to a shore station via a 1 kV submarine cable; since then, 12 WECs of this type have been built and tested at the site [27]. Because each generator produces a variable-frequency, variable-amplitude output, the WECs are rectified and interconnected in parallel through an offshore substation before being inverted and synchronized with the grid, which was achieved in November 2015, with further units added in 2017. Tests with non-linear loads and ultracapacitor filters demonstrated effective power smoothing, showing how aggregating multiple units reduces the need for storage [28,29].

A 2015 permit (valid until 2034) authorizes up to 20 devices and two substations, significantly expanding the experimental scope compared to the original permits. From the outset, the project has run systematic environmental monitoring of benthic and mobile fauna and biofouling, finding only a modest impact alongside positive artificial reef effects—foundations with cavities hosted notably more brown crabs even 12 years after deployment [30]. Lysekil thus stands as one of the world's longest-running and most comprehensive experimental programs for direct drive linear WECs. Figure 6 shows the Lysekil Project and Table 8 reports its main specifications.

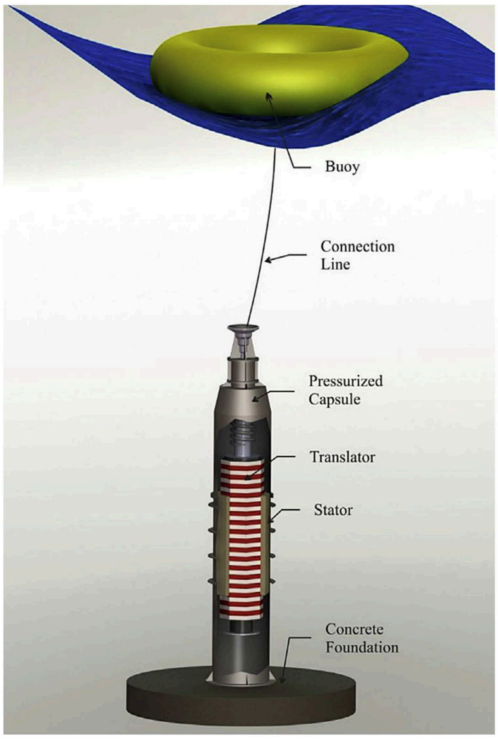



**Figure 6.** Illustration of the WEC developed at Uppsala University [28].

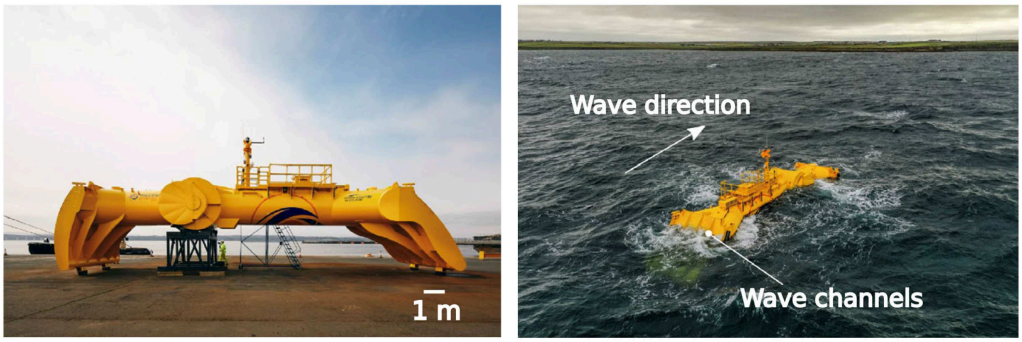
**Table 8.** General specifications of the Lysekil Project device.

| Parameter | Lysekil Project |
|---|---|
| Country | Sweden |
| Power | 10 kW/unit (nominal, prototype L1)<br>260 kW total (11 devices of varying sizes, 2024 data) |
| Depth | 24–25 m |
| Configuration | Point absorber + seabed-mounted linear generator |
| Mass | Buoy ~1 t (Ø 3 m × 0.8 m); seabed foundations ~10 t each; generator casing 5 m |
| PTO | Direct drive, three-phase synchronous permanent magnet linear generator (Nd-Fe-B) |
| TRL | 7–8 (full-scale at sea since 2006, 12 WEC tested, grid-connected since 2015) |
| Status | Operational (permit valid until 2034/2035) |

### 3.2. Attenuator

In the analysis of technologies related to attenuators, technical correlations were performed on the following devices: Mocean Energy Blue X.

The Blue X is a wave energy converter developed by the Scottish company Mocean Energy, based on hinged raft technology with significant innovations in geometric design. The device has successfully completed extensive open sea trials at the European Marine Energy Center (EMEC) in the Orkney Islands, Scotland [31]. The Blue X structure consists of two distinct sections joined by a central hinge. When a wave passes beneath the device, the two sections flex and rotate around the hinge; this relative motion is captured by an internal conversion mechanism, i.e., PTO, and converted into electricity [32]. Figure 7 shows the Mocean Blue X device, and Table 9 reports its main specifications.




(**a**) (**b**)

**Figure 7.** (**a**) Photo of the Mocean Energy Blue X full-scale device; (**b**) deployed at the European Marine Energy Center in Orkney, Scotland [33].

**Table 9.** General specifications of the Mocean Energy Blue X device.

| Parameter | Mocean Energy Blue X |
|---|---|
| Device type | Attenuator |
| Rated power | 10 kW |
| Design | Asymmetric geometry with submerged plates |
| Main application | Off-grid, subsea power |
| Test site | EMEC, Orkney Islands (Scotland) |
| TRL | 5–6 |
| Status | Testing completed in 2024 |

The Blue X's distinctive innovation lies in its asymmetrical geometry and the submerged plates at its ends. This configuration is designed to significantly enhance wave capture, with more power than traditional raft designs. The design's flexibility also allows the device to "dive" beneath larger waves during storms, reducing extreme forces and increasing survivability in hostile environments [34]. The primary role of the Blue X prototype was to demonstrate the feasibility of off-grid energy solutions for the offshore industry. The device was the centerpiece of the Renewables for Subsea Power project, which demonstrated how to combine wave energy with subsea storage (Verlume Halo batteries) and, in some cases, solar energy, to provide low-carbon power and communications to subsea assets. The main applications of the Blue X include:

- Powering underwater sensors and monitoring systems;
- Charging of Autonomous Underwater Vehicles (AUVs);
- Energy solutions for the oil, gas, and offshore wind sectors;
- Reduced reliance on umbilical cables and diesel generators.

The successful testing of the Blue X, which operated for months under real-world marine conditions, provided valuable data for development. The Blue Star device, derived from the Blue X, is specifically designed for commercial-scale underwater power supply applications [34].

### *3.3. Flexible Tube Devices*

Flexible tube devices are a type of wave attenuator consisting of long, elastic or expandable tubes filled with fluid and sealed at both ends, which float just below the surface. As waves pass over them, the tubes compress and deform, creating internal pressure waves (bulge waves) that propagate longitudinally. Energy can be extracted at the end of the tube via hydraulic turbines or, in advanced designs, through distributed conversion along the entire length using electroactive materials. Structural flexibility provides inherent survivability, allowing the device to deform under extreme loads.

In the analysis of technologies related to flexible tube devices, technical correlations were performed on the following devices: S3 WEC (SBM Offshore).

The S3 WEC is a wave energy converter developed by SBM Offshore, one of the world's leading companies specializing in offshore production and storage systems for the oil and gas industry. The entry of a marine engineering giant into the wave energy sector has lent significant credibility to the project, which is designed to be robust, scalable, and suitable for deep-water operations [35]. Unlike Generation 1 WECs—characterized by rigid and bulky structures, complex hydraulic systems, turbines, gearboxes, and hinges that require intensive maintenance and exhibit stress concentrations on the PTO components—the S3 represents a radical paradigm shift. The device is a long elastomeric flexible tube, entirely filled with water and hermetically sealed at both ends, which is moored to the seabed and operated in a submerged position [35]. The operating principle consists of the following stages:

- Wave–structure interaction: Ocean waves traveling along the length of the pipe induce external pressure variations that radially deform the elastomeric wall, exciting a system of internal standing waves. Thanks to the structure's multimodal behavior, the device responds efficiently to a wide range of wave periods, naturally attenuating sea roughness;
- Direct conversion via EAP: Electroactive Polymer (EAP) generators, more specifically Dielectric Elastomer Generators (DEG), are distributed along the entire length of the tube. These elements function simultaneously as structural material and as a PTO system: the cyclic mechanical deformation of the tube wall is converted directly into electricity, without any mechanical intermediary;

- Electrical output: EAP generators produce high-voltage direct current with low ripple, distributed throughout the structure to prevent stress concentrations on individual components [35].

The S3's key strength lies in the complete elimination of turbines, hydraulic components, hinges, gearboxes, and any other moving mechanical parts, resulting in the following direct benefits:

- No routine maintenance: a passive system with no conventional moving parts in contact with saltwater;
- Reduced production costs: the manufacturing process is based on roll-to-roll technology, borrowed from the high-voltage capacitor industry (EAPs share the same physical principles), which enables continuous, low-cost production;
- Operational flexibility: the tube can be rolled up or folded for transport and installation, reducing offshore logistics costs [35].

SBM Offshore has been conducting an extensive experimental development campaign since 2009. Tank tests, carried out at the company's in-house laboratory in Carros, France, and at the Danish Hydraulic Institute (DHI), have demonstrated the S3's ability to convert wave energy into electricity with high efficiency across a wide range of wave periods. The prototype for the sea trial, scheduled to take place in the waters of the Principality of Monaco starting in 2021, measured 60 m in length and 1.2 m in diameter, with a sea footprint of approximately 300 m × 80 m including moorings [35]. The objective was to verify the system's behavior under real-world conditions, the degradation of materials over time, and the performance of the conversion system, while simultaneously delivering the first kWh to the grid. The latest documented tests (SPIE 2025 conference) involved a prototype measuring 10 m × 1.2 m in diameter.

Despite the significant technical results achieved over more than a decade of R&D, SBM Offshore ultimately made the strategic decision to discontinue the S3 project, having failed to demonstrate a clear path to commercialization in its current form. The S3 nevertheless remains an important milestone in the development of flexible tube WECs with direct electroactive conversion, having demonstrated worldwide the feasibility of EAP technology applied to wave energy conversion in a marine environment [35]. Figure 8 shows the working principle of the S3 WEC (SBM Offshore), and Table 10 reports its main specifications.

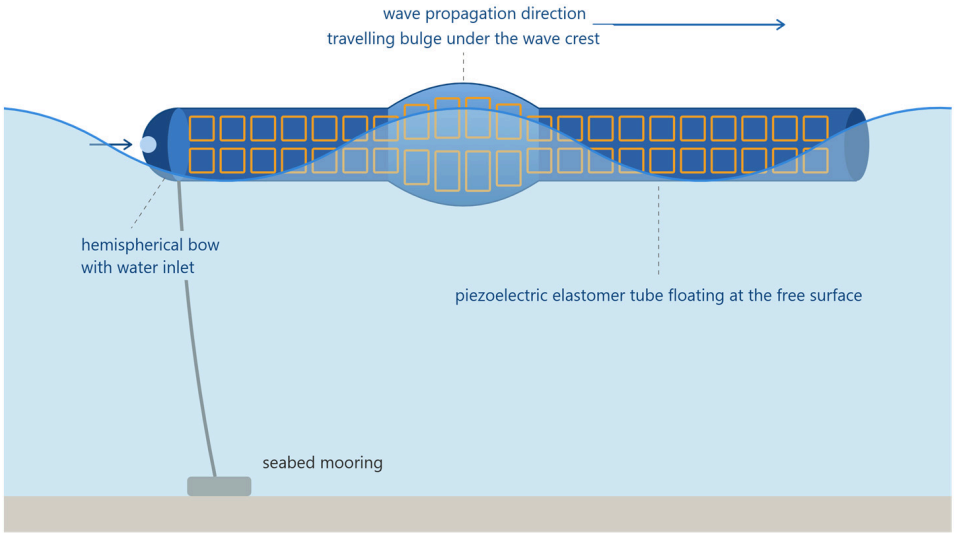



**Figure 8.** Working principle of S3 WEC (SBM Offshore). During wave propagation (see the arrow), the elastomeric body is deformed activating the dielectric generators (orange squares in the picture).

**Table 10.** General specifications of the S3 WEC device (SBM Offshore).

| Parameter | S3 WEC |
|---|---|
| Device type | Submerged elastomeric flexible tube device |
| Prototype scale | Not officially specified |
| Prototype length | 60 m (Monaco sea trial prototype)/10 m (final basin test prototype, SPIE 2025) |
| PTO system | Electroactive Polymers—Dielectric Elastomer Generators (EAP/DEG) |
| PTO position | Distributed along the entire tube length (PTO integrated into the structure) |
| Test site | Carros Laboratory, France (basin tests) + waters of the Principality of Monaco (sea trial, 2021) |
| Developer | SBM Offshore (Monaco/Netherlands) |
| TRL | 5–6 (scaled prototype tested in basin and at sea; commercialization not demonstrated) |
| Status | Development suspended (SBM Offshore abandoned the project in 2025) |

### *3.4. Gyroscope Systems*

Gyroscopic systems represent a category of WECs that utilize the gyroscopic effect to convert wave-induced oscillatory motion into electrical energy. Unlike conventional devices that interact directly with seawater through external surfaces, gyroscopic systems operate using rotating flywheels enclosed within a watertight hull. When wave motion induces rotations (pitch, roll) of the floating structure, the gyroscopic flywheel reacts with a precession movement that can be harnessed to generate electricity. This approach offers significant advantages in terms of protection against marine corrosion, absence of biofouling, and reduced hydrodynamic drag. In the analysis of technologies related to gyroscopic systems, technical correlations were performed on ISWEC.

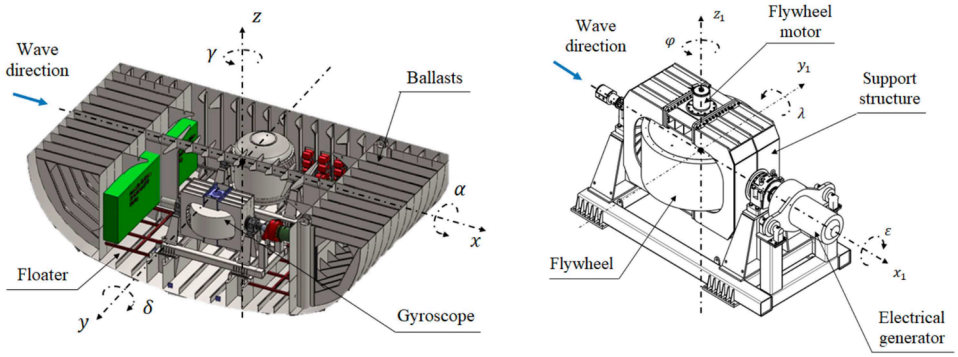
The ISWEC (Inertial Sea Wave Energy Converter) is a gyroscopic wave energy converter developed by the Polytechnic University of Turin in collaboration with Wave for Energy s.r.l. (a university spin-off) and Eni. The ISWEC represents one of the most advanced Made in Italy technologies for harnessing wave energy and, of fundamental importance for this study, is the only WAB device to have been tested and connected to the power grid in the Mediterranean basin [36]. The first ISWEC concept dates back to 2006 and was developed by the research group led by Giuliana Mattiazzo at the Department of Mechanical Engineering of the Polytechnic University of Turin. Following experimental validation in 2009 of a 1:45 scale prototype at the University of Edinburgh wave tank [36], the development progressed through subsequent scaled tests, leading to the deployment of the first full-scale device in 2015. In August 2015, the first pre-commercial prototype was installed 800 m off the coast of Pantelleria, at a depth of 35 m, marking the first full-scale Italian device for generating electricity from wave motion [37,38]. In March 2023, Eni announced the completion of the connection to the island's power grid, marking a world first in the wave energy sector with a peak power of 260 kW [37].

The operating principle of the ISWEC is based on the gyroscopic effect to solve the so-called "reaction problem" typical of WECs. Unlike conventional devices that react against the seabed, external structures, or directly against the water (exposing mechanical components to the hostile marine environment), the ISWEC uses an internal inertial mass to provide the reaction necessary for power extraction [36]. The system operates through the following stages:

- Wave excitation: ocean waves induce a pitching motion on the floating hull, which oscillates in response to the passing wave;
- Gyroscopic precession: the pitching motion is transmitted to the internal gyroscopic system, consisting of one or more high-speed rotating flywheels. In accordance with the laws of gyroscopic dynamics, the pitch torque induces a precession torque perpendicular to both the flywheel's axis of rotation and the pitch axis;

- Power extraction: the precession torque is captured by a Power Take-Off (PTO) system that converts the mechanical motion into electrical energy via a generator coupled to the precession axis (ε-axis) [36];
- Transmission to shore: the electricity produced is transferred to the terrestrial power grid via a submarine cable [37].

The ISWEC installed in Pantelleria consists of an 8 × 15 m steel hull that houses the energy conversion system, comprising two gyroscopic units, each with a diameter exceeding 2 m. The device is held in position by a special mooring system consisting of three mooring lines and a swivel that allows it to adapt to weather and sea conditions [37]. Figure 9 shows the internal components and mounting system of the ISWEC, and Table 11 reports its technical specifications.




(a) (b)

**Figure 9.** (**a**) View of the ISWEC hull; (**b**) View of the gyroscope showing its main components [39].

**Table 11.** ISWEC Technical Specifications.

| Parameter | ISWEC |
|---|---|
| Device type | Gyroscopic system |
| Peak power | 260 kW |
| Rated power (Ravenna pilot project) | 50 kW |
| Hull dimensions | 8 × 15 m |
| Emerging height | ~1 m |
| Installation depth | 35 m |
| Number of gyroscopic units | 2 |
| Flywheel diameter | >2 m |
| Mooring system | 3 lines+ a swivel |
| Distance from shore | 800 m |
| Test site | Pantelleria (Mediterranean Sea) |
| Developers | Politecnico di Torino, Wave for Energy, Eni |
| TRL | 7–8 |
| Status | Operational, grid-connected (2023) |

The key strengths of ISWEC technology include:

- Modularity: The gyroscopic unit can be scaled to adjust the converter's rated power, allowing adaptation to different site conditions;
- Reliability and durability: The entire conversion mechanism operates inside a watertight hull, protected from the hostile marine environment. No moving parts are exposed to saltwater, eliminating the corrosion and biofouling issues typical of conventional WECs;
- Adaptability: Energy production is maximized thanks to a control system based on meteorological and oceanographic data. The design can be optimized for the specific

conditions of the installation site using genetic algorithms that leverage the computing power of Eni's Green Data Center;
- Storm survivability: By shutting down the gyroscopic system, the ISWEC behaves like an inert floating body, significantly increasing the chances of survival in the event of extreme weather events [36];
- Low visual impact: The device protrudes only about 1 m above the water level, significantly reducing the visual impact compared to other offshore renewable technologies [37].

The ISWEC technology has been recognized by the European Commission in its strategy for offshore renewable energy as a key example of wave energy conversion. In addition to the installation close to Pantelleria, Eni, the Polytechnic University of Turin, and Wave for Energy have carried out a second pilot project with a nominal capacity of 50 kW in the waters off Ravenna, demonstrating the technology's versatility for various applications [37]. ISWEC is particularly well-suited for the Mediterranean context, characterized by generally lower waves than in the Atlantic. The technology is designed to harness wave slopes rather than their absolute height, making it ideal for enclosed seas where wave heights are moderate, but slopes can be significant [36]. Target applications include:

- Powering small, off-grid islands;
- Providing energy support for offshore infrastructure (oil and gas platforms, offshore wind farms);
- Integration with other marine renewable energy sources;
- Power supply for remote coastal communities.

### *3.5. Discussion, Summary of Results and Device Comparisons*

The following section provides a detailed analysis, comparing all the devices examined so far using specific tables to highlight their main technical characteristics, stage of development, etc., and concludes with an overall ranking of all the devices. Tables 12–15 compare the point absorbers, attenuators, flexible tube devices, and gyroscopic systems, respectively.

Across the ten devices, technological maturity remains varied (Tables 12–15). Point absorbers and gyroscopic systems form the high-maturity cluster: CorPower Ocean C4 and ISWEC have combined full-scale open-sea operation with grid connection, while the Lysekil array and CETO 5 provided earlier multi-month grid-connected demonstrations. The remaining converters—the Mocean Blue X attenuator and the SBM S3 flexible tube device—sit at an intermediate maturity (TRL 5–6), having completed sea or basin trials without reaching commercial demonstration. The mass-to-power ratio is the most consistently reportable proxy for capital intensity, and it separates two opposing design philosophies: compact resonant point absorbers minimize structural mass per unit power (CorPower C4 $\approx$ 200 t/MW; the direct drive Lysekil buoys are of the same order), whereas the multi-absorber Nankun platform reaches $\approx$ 6000 t/MW, trading material efficiency for robustness and multi-functionality.

**Table 12.** Specifications and Features of Point Absorbers.

| Parameter | CP C4 | CP C5 | OPT PB 2.0 | CETO 5 | CETO 6 | Nankun | Lysekil |
|---|---|---|---|---|---|---|---|
| Power | 300 kW | 1.5 MW | 4.1 kW (solar) | 240 kW | 1.5 MW | 1 MW | 10 kW/unit |
| Mass (t) | 60 | / | 13–16 | / | / | 6000 | buoy ~1 t (Ø3 m × 0.8 m); seabed foundation ~10 t/unit |
| Mass to power ratio (t/MW) | 200 | / | / | / | / | 6000 | ~100 (floating buoy only)/~1100 (incl. seabed foundation) |

**Table 12.** *Cont.*

| Parameter | CP C4 | CP C5 | OPT PB 2.0 | CETO 5 | CETO 6 | Nankun | Lysekil |
|---|---|---|---|---|---|---|---|
| Depth | 45 | / | Variable | Sub-surface | Sub-surface | Sub-surface | 24–25 m |
| TRL | 7 | 5–6 | 7 | 7 | 5–6 | 6 | 7–8 |
| Status | Operational | Planned | Operational | Completed | Under development | Test | Operational |
| Configuration | Surface (floating) | | | Sub-surface (submerged) | | Surface platform | Surface buoy + seabed-mounted linear generator |
| PTO | Mechanical (Gearbox) + WaveSpring | | Internal mechanical | Hydraulic (onshore pumping) | Electric (onboard generators) | Hydraulic | Direct drive PM (Nd-Fe-B) linear generator (no gearbox/hydraulics) |
| Application | Grid-scale, wave farms | | Off-grid, subsea power | Grid-scale, microgrid | Grid-scale, remote island | Grid-scale, aquaculture | Grid-scale research array |
| Additional functions | / | / | IoT, communications, surveillance | Desalination | Microgrid integration | Desalination, solar panels | Environmental monitoring/artificial reef studies |
| Key features | Active phase control, resonance amplification | | Multi-source (wave + solar + wind) | High-pressure water, integrated desalination | No pipelines, cable transmission | Hydraulic rods, centralized conversion | No intermediate conversion stage; longest-running direct drive WEC test site |
| Year of deployment | 2023 | 2026–2027 (planned) | 2023–2024 | 2015 | Canceled in 2019 | 2023 | 2006 (first unit); grid-connected 2015 |
| LCOE (€/MWh) | ≈282–310 [40] | Offshore-wind parity | N/A | N/A | N/A | N/A | N/A |
| CAPEX | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

The single full-scale C4 is rated TRL 7, consistent with the HiWave-5 roadmap (Stage 4, 2020–2022, TRL 6 → 7) and the ongoing DNV certification; TRL 8 is reserved for the certified pilot array (Stage 5). Nankun is rated TRL 6: it completed open-sea testing in 2023, but sustained, certified grid-connected operation has not yet been demonstrated. CorPower C5 is rated TRL 5–6: component-level design is complete, but the first pilot-array demonstration is scheduled for 2026–2027 (HiWave-5 project); as no at-sea testing has yet taken place, the device cannot be rated above pre-demonstration level. OPT PowerBuoy 2.0 is rated TRL 7: OPT completed long-term open-sea testing in September 2024, confirming operational performance under real-world conditions, though not yet at grid-connected commercial scale. CETO 5 is rated TRL 7: the device operated successfully for over a year in a real sea environment before decommissioning. CETO 6 is rated TRL 5–6: the Albany Wave Energy Project, intended to demonstrate the 1.5 MW commercial-scale unit, was canceled in March 2019 before real-sea deployment; the device therefore never reached the demonstration stage achieved by CETO 5. Lysekil is rated TRL 7–8, as detailed directly in Table 8: full-scale operation at sea since 2006, 12 WEC units tested and grid-connected since 2015. LCOE and CAPEX are reported only where publicly disclosed or available from published techno-economic studies; "N/A" denotes values not released by the developers.

**Table 13.** Specifications and features of attenuators.

| Parameter | Blue X |
|---|---|
| Power | 10 kW |
| Application | Off-grid subsea power |
| TRL | 5–6 |
| Status | Completed |
| Year of deployment | 2021 (sea trial) |
| LCOE | N/A |
| CAPEX | N/A |

Blue X is rated TRL 5–6: the device completed months of real-sea open trials at EMEC, but testing concluded in 2024 without progressing to certified, sustained commercial deployment; the successor Blue Star, intended for commercial-scale application, has not yet been tested at sea.

**Table 14.** Specifications and features of flexible tube devices.

| Parameter | S3 WEC |
|---|---|
| Power | N/A |
| Length (m) | 10 (prototype) |
| Material | Elastomeric flexible tube |
| PTO | EAP/DEG (distributed direct conversion) |
| PTO position | Above buoyancy line |
| TRL | 5–6 |
| Status | Suspended |
| Year of deployment | 2021 (sea trial) |
| LCOE | N/A |
| CAPEX | N/A |

S3 WEC is rated TRL 5–6: despite over a decade of tank testing and a partial sea-trial campaign (from 2021, most recently reported at the SPIE 2025 conference), the developer (SBM Offshore) ultimately discontinued the project without demonstrating a clear commercialization pathway; the device therefore remains at a pre-commercial demonstration level.

**Table 15.** Specifications and features of gyroscope systems.

| Parameter | ISWEC |
|---|---|
| Power | 260 kW (peak) |
| Scale | Grid-scale |
| TRL | 7–8 |
| Mediterranean test | Yes (Pantelleria) |
| Primary application | Off-grid island, offshore |
| Key innovation | Watertight hull + adaptive control |
| Wave motion exploited | Pitch |
| PTO mechanism | Precession → Generator |
| Flywheel | 2 units, Ø > 2 m |
| Irregular wave adaptability | Active control (genetic algorithms) |
| Developer | Politecnico di Torino/Eni |
| Status | Operational (grid-connected) |
| Year of deployment | 2015 (full-scale); grid-connected 2023 |
| LCOE | See techno-economic study |
| CAPEX | N/A |

For ISWEC, a genetic algorithm techno-economic optimization has estimated its achievable LCOE [41]. ISWEC is rated TRL 7–8: the device has been grid-connected and operational off Pantelleria since 2023, with a second 50 kW pilot deployed off Ravenna, demonstrating replicability across sites; TRL 9 (full commercial fleet deployment) has not yet been reached.

Device-specific LCOE and CAPEX are seldom disclosed, which is why these fields are largely reported as N/A in Tables 12–15; nonetheless, the literature provides robust archetype ranges. Most published estimates place wave energy LCOE between about 300 and 1200 €/MWh, well above offshore wind (50–80 €/MWh) [40]. Within this range, technology and site jointly govern competitiveness: applying the same techno-economic model, the attenuator Pelamis was estimated at ~736 €/MWh along the Portuguese coast, whereas for a resonant point absorber of the CorPower family it was evaluated between 282–310 €/MWh at favorable island sites such as Lanzarote and Bora Bora [40]. CAPEX is dominated by the primary structure and the mechanical/electrical components, and first-array commercial estimates remain high. The literature converges on three compounding cost reduction levers—economies of scale and array deployment, integrated WEC–PTO–control co-design, and learning-by-doing—projected to bring wave LCOE down to about €110/MWh at utility-scale deployment by 2030, consistent with the SET-Plan wave target of €150/MWh and contingent on the ~3 GW of ocean energy capacity targeted in Europe by that date [42].

Beyond cost, suitability to the target wave climate is decisive. High-energy Atlantic and North Sea sites (annual mean flux typically 20–60 kW/m) favor large, robust converters, whereas the Mediterranean is markedly less energetic and strongly seasonal: mean wave power reaches up to ~15 kW/m only off western Sardinia, about 8–9 kW/m in the Sicily Channel and falls below 3 kW/m in the Adriatic, with 12–24 kW/m in winter against 1–6 kW/m in summer [8,43]. In this regime, omnidirectionality, compactness and the ability to exploit wave slope rather than absolute height matter more than raw power capture. These requirements explain why ISWEC, the only WAB device grid-connected in the basin, and compact omnidirectional point absorbers (CorPower family) are, in our assessment, the most promising Mediterranean candidates, whereas large attenuators optimized for long Atlantic swells are comparatively penalized.

To synthesize the results quantitatively rather than descriptively, each device was scored on a 1–5 scale against the four equally weighted performance criteria defined in Section 2.5: technological maturity (TRL), mass-to-power ratio, demonstrated survivability, and Mediterranean suitability, with criteria for which no public evidence was retrieved recorded as n.d. and excluded from the score (Table 16). Devices are therefore characterized by a score range rather than by a single total, and the availability of techno-economic evidence is reported alongside the scores without contributing to them.

The assessment confirms the qualitative picture. The resonant point absorber CorPower C4 leads under every assumption (20–20), ahead of the long-running direct drive Lysekil array (18–18) and the grid-connected ISWEC, whose range (16–20) overlaps both and reflects the fact that its hull mass has not been publicly reported. At the opposite end, the multi-absorber Nankun platform ranks lowest on fully documented evidence (8–8), owing to its mass-to-power ratio and its limited suitability for the Mediterranean wave climate, whereas the flexible tube S3 spans 8–12 because part of its evidence base is unavailable rather than unfavorable.

The ranking should be read as a transparent and reproducible summary of the published record rather than as an absolute verdict. It depends on the equal-weighting choice and, for devices with partial coverage, on information that developers have not disclosed: re-weighting the criteria, for example toward Mediterranean suitability, or the release of currently withheld mass and cost data would shift the order accordingly. Devices whose ranges overlap should not be regarded as separable on present evidence. The detailed scoring scale is reported in the table footnote.

**Table 16.** Evidence-based multi-criteria assessment of the ten analyzed WAB devices. Each performance criterion is rated 1–5 with equal weights; criteria for which no public evidence was retrieved are recorded as n.d. and excluded from the score (see Section 2.5).

| Device | Maturity | Mass/Power | Surviv | Medit | Score Range | Tier | Coverage | Econ. Evidence |
|---|---|---|---|---|---|---|---|---|
| CorPower C4 | 5 | 5 | 5 | 5 | 20–20 | A | 4/4 | Literature estimate |
| Lysekil | 5 | 5 | 5 | 3 | 18–18 | B | 4/4 | Not disclosed |
| ISWEC | 5 | n.d. | 5 | 5 | 16–20 | B-A | 3/4 | Literature estimate |
| Carnegie CETO 5 | 5 | n.d. | 5 | 3 | 14–18 | C-B | 3/4 | Not disclosed |
| OPT PowerBuoy 2.0 | 5 | n.d. | 5 | 3 | 14–18 | C-B | 3/4 | Not disclosed |
| CorPower C5 | 3 | n.d. | 3 | 5 | 12–16 | C-B | 3/4 | Developer target only |
| CETO 6 | 3 | n.d. | 5 | 3 | 12–16 | C-B | 3/4 | Not disclosed |
| Blue X | 3 | n.d. | 3 | 3 | 10–14 | D-C | 3/4 | Not disclosed |
| S3 WEC | 3 | n.d. | 3 | 1 | 8–12 | D-C | 3/4 | Not disclosed |
| Nankun | 3 | 1 | 3 | 1 | 8–8 | D | 4/4 | Not disclosed |

Scoring (Section 2.5). Each performance criterion is rated on a 1–5 scale.

Maturity—1: TRL 2–3; 3: TRL 4–6; 5: TRL 7–9.

Mass-to-power—5: <500 t/MW; 3: 500–2000 t/MW; 1: >2000 t/MW as documented. Ratios are computed on the primary floating structure at rated power, consistently excluding moorings, anchors, and seabed foundations, which are not reported for most devices.

Survivability—5: demonstrated storm survival at sea; 3: explicit storm protection strategy documented; 1: absence of a protection strategy documented in the source material.

Mediterranean suitability—5: high (omnidirectional, compact, slope-driven); 3: medium; 1: low. This criterion reflects a qualitative assessment by the authors against the wave climate characteristics discussed in Section 3.5, and is not derived from site-specific power matrix modeling.

n.d.—no public evidence was retrieved for the criterion. Such criteria are excluded from the score and are not assigned the minimum value: a score of 1 denotes documented low performance, never absence of information.

Coverage—number of performance criteria supported by public evidence, out of four. It indicates how much of each device's position rests on documented data.

Score range—the lower bound is obtained by assigning the minimum value (1) to every n.d. criterion, and the upper bound by assigning the maximum value (5); the four-criterion sum ranges from 4 to 20. Devices with full coverage have a single-valued range. The width of the range measures the residual uncertainty due to undisclosed data, and devices whose ranges overlap are not separable on the available evidence.

Tier—A: $\geq$19; B: 15–18; C: 11–14; D: $\leq$10, assigned on the lower bound and reported as a span where the range crosses a band boundary.

Econ. evidence—descriptive only, not scored. Disclosed figure/independent literature estimate/developer target only/not disclosed.

## 4. A Brief Overview of PTOs

The performance and economic viability of the WAB devices analyzed in Section 3 are, to a large extent, governed by the design of their Power Take-Off system: the same wave-capture geometry can yield markedly different power output, survivability, and cost depending on how the captured mechanical energy is converted into electricity. This section therefore reviews the main PTO architectures identified across the analyzed devices—hydraulic, direct drive electric, and electroactive/dielectric elastomer generator (EAP/DEG)—as the shared enabling subsystem underlying the four WAB categories discussed above.

The Power Take-Off (PTO) is the subsystem that converts the mechanical energy extracted from wave motion into usable electricity and, more than any other component, governs the overall efficiency, reliability, and cost of a Wave Energy Converter [44]. Because it must operate under low-frequency, irregular, and high-amplitude loads in a hostile marine environment, the PTO is also the main source of the performance and survivability differences observed among the WAB devices analyzed in Section 3. The literature identifies a limited set of PTO architectures—hydraulic, direct drive electrical, mechanical (including emerging solutions), and, for flexible tube converters, distributed electroactive conversion [45]—each associated with a distinct efficiency range and a specific class of devices. This section briefly summarizes these architectures, relates them to the converters reviewed here, and highlights the most relevant recent advances. The main PTO families adopted by the reviewed devices are summarized in Table 17, and their working principles are illustrated schematically in Figure 10.

**Table 17.** PTO architectures of the WAB devices analyzed in this review, with operating principle and typical conversion efficiency.

| PTO Type | Operating Principle | Typical Efficiency | Devices in This Review |
|---|---|---|---|
| Hydraulic | Cylinders/pumps convert the oscillatory motion into high-pressure fluid driving a hydraulic motor or turbine; accumulators smooth the flow | 40–60% | CETO 5, Nankun |
| Mechanical (rotary) | Gearbox, rack-and-pinion or ball screw converts oscillatory motion into unidirectional rotation of a generator | 65–70% | CorPower C4/C5; OPT PowerBuoy 2.0; Mocean Blue X |
| Direct drive electrical | Primary body coupled directly to a permanent magnet linear generator, with no intermediate stage | 60–70% | Lysekil; CETO 6 |
| Gyroscopic (precession) | Hull pitch induces flywheel precession that drives a sealed rotary generator; no parts exposed to seawater | Device specific | ISWEC |
| Distributed electroactive (EAP/DEG) | Dielectric elastomer generators embedded in the deforming tube wall convert strain directly into electricity | Emerging (not yet consolidated) | S3 |

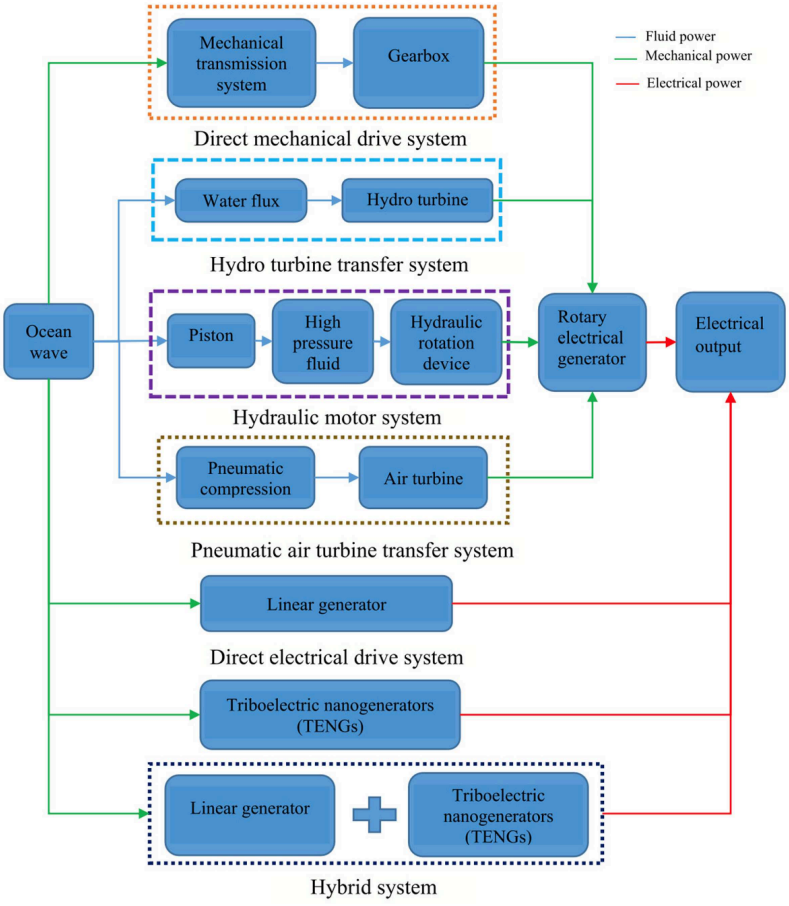



**Figure 10.** Working principles of the PTO categories [46].

### 4.1. Types

Table 17 summarizes the PTO architectures adopted by the devices reviewed here, together with their operating principles and the typical conversion efficiency reported in the literature [44,45]. Five families are represented: hydraulic, mechanical (rotary), direct drive electrical, gyroscopic precession, and distributed electroactive conversion—each associated with a distinct efficiency range and a specific group of converters. Pneumatic air turbine PTOs, characteristic of oscillating water column devices, fall outside the WAB scope of this review and are therefore not discussed.

### 4.2. State of the Art

Recent PTO research has focused on integrated design and control rather than on individual components. Co-design of the WEC structure, PTO, and control through genetic algorithms has been shown to cut the LCOE by up to a factor of six when capacity is scaled from 10 kW to 1 MW [47], while power optimization modeling tools balance power maximization against CAPEX in the sizing of adjustable generators [48]. On the conversion side, active-clutch mechanical motion rectifiers and over-actuated, multi-degree-of-freedom architectures have raised the capture width ratio beyond the single-DOF limit (up to CWR $\approx$ 0.47) and improved power output by 10–30% near resonance [49,50], while mooring PTO co-optimization adds a further ~10% broadband gain [51]. Full-scale validation, however, remains the critical bottleneck: field measurements on a deployed converter showed that conventional PTO models can overestimate energy output by up to a factor of three unless generator inertia and speed-dependent friction are explicitly included [52].

### 4.3. Challenges and Development Needs

The performance of PTO systems is assessed with a consistent set of metrics—Capture Width Ratio, mean-to-peak power ratio, and LCOE [44,46]; yet several obstacles still separate laboratory results from bankable devices. Long-term durability and reliability in a corrosive, high-load environment remain the dominant concern, particularly for hydraulic circuits exposed to leakage and for the elastomeric materials of electroactive converters, while offshore operation and maintenance weigh heavily on OPEX and therefore on LCOE [46]. Scaling prototypes to commercial size introduces further uncertainty, as shown by the up-to-threefold gap between idealized models and field measurements [52]. Priority research directions are the integrated optimization of the WEC–PTO–mooring–control chain [50,51], high-fidelity modeling of PTO non-linearities (friction, hysteresis, magnetic saturation), advanced lightweight and anti-fouling materials, and AI-based real-time control with predictive maintenance. Overall, the PTO landscape is technologically rich but still requires standardization and full-scale validation to reach cost parity with other renewable sources.

## 5. Conclusions and Perspectives

This systematic review analyzed ten Wave-Activated Body (WAB) devices distributed across four representative subcategories—point absorbers, attenuators, flexible tube devices, and gyroscopic systems—and complemented the device-level analysis with an overview of Power Take-Off (PTO) systems. The comparative framework was built on technological maturity, energy performance, mass-to-power ratio, and applicability to the Mediterranean basin.

The results address the three objectives stated in the introduction. Point absorbers and gyroscopic systems represent the most mature WAB classes, with CorPower Ocean C4 reaching TRL 7 and ISWEC TRL 7–8, both grid-connected in real sea conditions; attenuators and flexible tube devices remain at intermediate or low TRLs (5–6), with several concepts

still in the prototyping or simulation phase. The mass-to-power ratio emerges as the discriminating indicator of economic competitiveness: compact resonant designs such as the C4 (~200 t/MW) demonstrate that intensive use of active phase control and storm survival strategies can drastically reduce structural mass per unit of installed capacity, in contrast with multi-absorber platforms exceeding 6000 t/MW. The literature on PTO co-design further confirms that the integrated optimization of WEC structure, PTO, and control plays a central role in reducing the overall LCOE. Within the Mediterranean context, ISWEC has demonstrated that gyroscopic architectures designed to exploit wave slope rather than absolute wave height are well suited to the moderate but persistent wave regimes of the basin, while compact point absorbers and hybrid wave–solar–wind platforms emerge as promising candidates for off-grid island applications.

From a technological standpoint, the most credible near-term progress will come from the resonant point-absorber and gyroscopic lines that already operate at sea. For these, the priority is no longer proof of concept but type certification and multi-year reliability demonstration over arrays of devices: CorPower Ocean's HiWave-5 array (one C4 and three C5 units, 4.8 MW, under DNV certification) and the scaling of ISWEC are the bellwether projects whose field data will determine whether TRL 8–9 and bankability are reached within this decade.

At the system level, the transition from single devices to wave farms is the decisive economic step. Techno-economic analyses show that the LCOE falls steeply with array size and with integrated WEC–PTO–control co-design, by up to a factor of six when capacity is scaled from 10 kW to 1 MW [47]. The research agenda should therefore prioritize array-level control, shared moorings and grid infrastructure, and standardized operation and maintenance. If the sector's deployment targets are met (Ocean Energy Europe envisages around 3 GW of ocean energy capacity in Europe by 2030), wave LCOE is projected to fall to roughly €110/MWh, approaching the SET-Plan target of €150/MWh and narrowing the gap with offshore wind [42].

The flexible tube, electroactive polymer approach, represented here by the SBM S3, remains the higher-risk, higher-reward frontier. Its promise of low material cost, inherent storm resilience, and distributed conversion without rotating machinery is still conditional on demonstrating the long-term durability of elastomers in seawater and the large-scale conversion efficiency of dielectric elastomer generators. Targeted accelerated aging programs and full-scale sea trials, rather than further conceptual studies, are the missing steps for this class.

For the Mediterranean specifically, the perspective is one of niche-first deployment. Given a resource that exceeds 10 kW/m only in limited northwestern areas and is strongly seasonal [43], the realistic short-term markets are off-grid and weak grid islands, aquaculture and offshore platform supply, and integration with offshore wind and solar, where wave energy displaces expensive diesel rather than competing head-to-head with utility-scale renewables. ISWEC-type slope-exploiting gyroscopes, compact omnidirectional point absorbers and hybrid wave–solar–wind platforms (such as PowerBuoy 2.0) are the device families best matched to these markets; site-specific LCOE assessments coupling local wave climate hindcasts with device power matrices, still largely missing for Mediterranean sites, should be a research priority.

This review has several limitations that should be acknowledged. First, the multi-criteria scoring scheme (Section 2.5, Table 16) reflects an equal-weighting choice among four performance criteria; a different weighting scheme, motivated for example by a specific application context, would alter the relative ranking of devices. Second, comparable performance and economic data are not uniformly available across the ten devices analyzed: LCOE and CAPEX figures, in particular, are disclosed for only a minority of the technologies,

and the resulting score ranges in Table 16 explicitly quantify this residual uncertainty rather than concealing it. Third, the Mediterranean suitability criterion reflects a qualitative assessment by the authors based on published wave climate data, rather than site-specific power matrix modeling; quantitative, site-specific LCOE assessments, as noted above, remain a priority for future work. These limitations do not affect the qualitative conclusions drawn above but should be considered when using the ranking in Table 16 for technology selection purposes.

In summary, wave energy is moving from device demonstration toward array-scale bankability. Among WAB converters, compact resonant point absorbers and gyroscopic systems are currently the most mature and economically promising classes; the mass-to-power ratio and array-level co-design are the principal cost levers; and a niche-first strategy, beginning with island and offshore platform markets, is the most realistic route to the first commercial Mediterranean wave farms. The following abbreviations and symbols are used in this manuscript and listed in Table 18:

**Table 18.** List of the main abbreviations used throughout the manuscript.

| Abbreviation | Definition |
|---|---|
| WEC | Wave Energy Converter |
| WAB | Wave-Activated Body |
| PTO | Power Take-Off |
| TRL | Technology Readiness Level |
| LCOE | Levelized Cost of Energy |
| CAPEX | Capital Expenditure |
| OPEX | Operational Expenditure |
| OWC | Oscillating Water Column |
| OWSC | Oscillating Wave Surge Converter |
| CWR | Capture Width Ratio |
| DOF | Degree of Freedom |
| EAP | Electroactive Polymer |
| DEG | Dielectric Elastomer Generator |
| ISWEC | Inertial Sea Wave Energy Converter |
| EMEC | European Marine Energy Center |
| IEA–OES | International Energy Agency—Ocean Energy Systems |
| PRIMRE | Pacific Region Integrated Marine Renewable Energy |
| Nd-Fe-B | Neodymium–iron–boron (permanent magnet material) |

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