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Floating Offshore Renewable Energy Farms. A Life-Cycle Cost Analysis at Brindisi, Italy

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Abstract: The present paper deals with the Life-Cycle Cost (LCC) of an offshore renewable energy farm that is currently a topic of interest for operators and investors. The LCC analysis refers to the Cost Breakdown Structure (CBS) considering all the phases of life span, and it has been carried out for floating offshore wind farms (FOWFs) and hybrid wind-wave farms (HWWFs). For HWWFs, this paper proposes a hybrid wind-wave energy system (HWWES), which provides the coupling of wave energy converter (WEC) with Tension Leg Platform (TLP) or Spar Buoy platform (SB). The LCC analysis has been carried out considering: (i) FOWF consisting of TLP floating platforms; (ii) FOWF consisting of a SB floating platforms; (iii) HWWF realized with the conceived hybrid system coupling the WEC with the TLP platform; (iv) HWWF realized with the conceived hybrid system coupling the WEC with SB platform. In addition to the LCC evaluation, the Levelized Cost of Energy (LCOE) analysis has also been carried out. The site chosen for the study is off the port of Brindisi, southern Italy. This work's interest lies in having performed a LCC analysis for FOWF and HWWF in the Mediterranean that is an area of growing interest for offshore renewable energy, and obtained results have allowed making assessments on costs for offshore energy farms.

Keywords: life-cycle cost analysis (LCC); LCOE; offshore wind energy; offshore wave energy; hybrid wind-wave system

1. Introduction

Offshore wind energy is considered to have great potential for growth, and it is expected to become one of the main renewable sources of energy [1,2].

The offshore wind farms currently operating employ fixed foundation in shallow water. In recent years, Research and Development (R&D) activities have increased considerably with several models under development and experimentation also for deep water. At deep water, the supporting structures for wind turbines are floating type, and the main typology are the Semi-Submersible (SS), the Tension Leg Platform (TLP), and the Spar Buoy (SB). Regarding the SS platform, several studies and projects are under development [3–5], and a review can be found in Liu et al. (2016) [6], while for the TLP typology, most of the projects are still in the scale test phase [7–10]. Regarding the SB platform, several studies have been carried out in recent years on this typology [11–15] and in October 2017, the world's first floating wind farm, the 30 MW "Hywind Scotland," became operating (https://www.equinor.com). Recent reviews on floating wind turbines can be found in [16–18].

Regarding the sea wave energy, different types of WEC have been developed in relation to the different ways in which energy can be absorbed by waves and also in relation to the depth of the water and the location [19]. Based on working principle, wave energy systems can be classified in an oscillating water column (OWC), oscillating bodies, and overtopping [19]. Studies and reviews on wave energy technologies can be found in [20–22].

HWWES, which combines a floating wind turbine (FWT) and WEC, is still in the initial stage. The advantages of HWWES are related to sharing mooring systems, electrical infrastructure, and other components of the wind turbine platform with a reduction of the overall costs. WECs could determine a reduction in the costs of offshore wind farms as operating and maintenance costs are shared, while offshore wind farms could lead to a reduction in the cost of wave energy production through the sharing of grid connection, logistics, and all the common infrastructures [23]. Studies on different concepts of HWWES have been carried out with numerical and experimental analysis, both with offshore wind turbine installations in shallow waters with fixed foundations and installations in deep waters with the main three types of floating platforms [24–31].

Considering the growing developments of FWTs and sea wave technologies, the analysis of the economic feasibility of the projects and on investment profits is currently a topic of interest. For operators, developers, and investors LCC considerations are of increasing importance to make evaluations for FOWF, wind-wave farms, and HWWF projects.

The LCC analysis is an evaluation method that allows determining the global cost of a product considering its entire life cycle, from the study to the design, up to the disposal phase, according to a cradle-to-grave approach. LCC techniques have successfully been applied in many capital-intensive activities to optimize investments. LCC analysis is also receiving increasing interest in the offshore renewable energy sector due to the growing investments in new wind projects and wave technology.

Castro-Santos and Diaz-Casas (2014) [32] presented a methodology to evaluate the Cost Breakdown Structure (CBS) [33] of a FOWF; CBS was evaluated linked to Life Cycle Cost System (LCS) and taking into account each of the six phases of the FOWF life cycle: Definition, design, manufacturing, installation, exploitation, and dismantling. Each of these costs was subdivided into different sub-costs. The case study refers to a floating offshore wind farm composed of 21 wind turbines located in Galicia, North-West of Spain. Three different floating platforms were considered: SS, TLP, and Spar-Buoy.

Myhr et al. (2014) [34] presented an analysis and comparison of the levelized cost of energy (LCOE) for five floating wind turbine concepts: SB ("Hywind II" concept), TLP ("SWAY" concept), SS ("WindFloat" concept), Tension-Leg-Wind-Turbine ("TLWT" concept), and Tension-Leg-Buoy ("TLB" concept).

Thomson and Harrison (2015) [35] estimated the Life Cycle Cost and carbon emission of offshore wind technology considering four life stages: Manufacturing, transport and installation, operation and maintenance, dismantling, and disposal.

Ioannou et al. (2017) [36] presented a study aimed at expanding the deterministic cost of energy model to account for stochastic inputs. Authors performed Monte Carlo simulations to derive the joint probability distribution of LCOE, allowing for the estimation of probabilities of exceeding set thresholds of LCOE determining certain confidence intervals.

Regarding WEC technology, in 2010, the U.S. Department of Energy initiated the development of six marine and hydrokinetic energy converter reference models of which three are wave energy converters. The methodology to calculate the levelized cost of energy and a comparison of the cost of energy have been presented in [37].

In Castro-Santos et al. [38], a methodology for LCC analysis for offshore renewable energy farms was presented. Two floating offshore renewable energy devices were presented; the first was based on wind energy technology, while the second one is based on wave energy technology. In a later study, the economic feasibility of offshore wave energy farms on the Portuguese continental coast has been presented by [39]. In the present study, three WEC devices have been taken into account.

However, currently, there are not many studies on the economic analysis for wind farms and even less for structures for wave energy production. To the authors' knowledge in the literature, there are no complete studies on the economic analysis for HWWES. There is limited experience, therefore, on the economic feasibility assessments for offshore renewable energy farms due to the low availability of data and to the high degree of uncertainty.

In this context, this paper presents an LCC analysis for FOWFs and HWWFs throughout their life span. The CBS method [33] and the LCC approach for offshore renewable energy farm described in [32,38,39] have been used as a guideline, and its structure is described in the Method Section in detail.

The LCC analysis has been carried out considering the case study of: (i) FOWF consisting of seven TLP floating platforms; (ii) FOWF consisting of seven SB floating platforms; (iii) HWWF realized with the conceived hybrid system coupling the WEC with TLP platform; (iv) HWWF realized with the conceived hybrid system coupling the WEC with SB platform.

Regarding the hybrid system, a proposal for a combination of wind and wave technologies has been presented in this paper, as described in detail in Section 2.

In addition to the LCC evaluation, an LCOE analysis has also been carried out.

The sites chosen for the study are off the port of Brindisi in the Apulia region, southern Italy.

The novelty of this study is related to the LCC analysis for an offshore HWWF in order to highlight the possible cost reduction thanks to the sharing of the platform, mooring, anchoring, etc. It is also the first study on economic feasibility for a renewable energy farm carried out in the Mediterranean that is becoming an area of increasing interest for wind and wave energy [40–43]. Finally, the chosen study area, the Apulia region, is an interesting area as it is an Italian region that is investing capitals in offshore wind energy; in fact, offshore Taranto, it has been decided that in the next few years will be operational the first offshore wind farm of Italy and one of the first of Mediterranean.

2. Structures Characteristic Data

The following section describes: The turbine characteristic data; the structural characteristics of the TLP and SB platforms; the conceived HWWES; the structural characteristics of the WEC device.

2.1. Turbine Characteristic Data

Regarding the turbine's model, a NREL-5MW has been considered [44]. To create the model, authors [44] obtained some broad design information from the published documents of turbine manufacturers, with a heavy emphasis on the REpower 5M machine and from other conceptual models. The characteristics of the turbine are shown in the following table (Table 1).

Table 1. Turbine characteristic data

Characteristics	Value	Unit
Rated power	5	MW
Turbine diameter	126	m
Hub Height	90	m
Rotor Mass	110	kg
Nacelle Mass	240	kg
Tower Mass	347.5	kg
Turbine Mass	697.5	kg

2.2. Structural Characteristics of TLP and SB Platform

The TLP floating platform considered is the one described in Zhou et al. (2016) [45], while for the SB platform, the reference is the structure described in [32]. Platform volume and mass of the TLP structure and floater volume of SB platform have been calculated by authors considering dimensions, while weight of anchoring and weight of mooring have been calculated considering installation depth of the platform [46]. Table 2 summarizes the structural characteristics of the two structures.

Table 2. Structural characteristics of Tension Leg Platform (TLP) and Spar Buoy (SB) platforms.

Characteristics	Value	Units	Reference
TLP platform			
Floater diameter	20	m	Zhou et al. 2016 [45]
Floater height	10	m	Zhou et al. 2016 [45]
Outrigger length	20	m	Zhou et al. 2016 [45]
Outrigger cross sectional area	16	m^2	Zhou et al. 2016 [45]
Platform volume	8345	m^3	Calculated
Platform mass	991410	kg	Calculated
Weight of anchoring	10530	kg	Calculated
Weight of mooring	2630	kg	Calculated
SB platform			
Number of mooring lines	3	-	Catro-Santos et al. [32]
Platform mass	988797	kg	Catro-Santos et al. [32]
Floater volume	8323	m^3	Calculated
Weight of anchoring	10530	kg	Calculated
Weight of mooring	2408	kg	Calculated

2.3. Description of HWWES and Structural Characteristics of WEC Device

The conceived HWWES provides the coupling of the WEC wave-type generator ("wave riding arms" type) with the TLP or SB floating platform. Figure 1 shows the hybrid system obtained by coupling the WEC with the TLP platform and the hybrid system obtained by coupling the WEC with the SB platform.

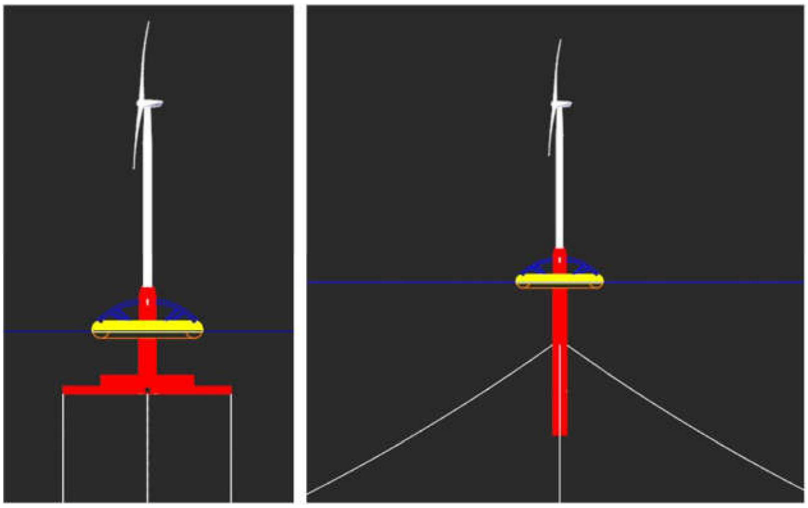

Figure 1. Conceived hybrid wind-wave energy system (HWWES): Wave energy converter (WEC) coupled with the TLP type platform (**left**); WEC coupled with SB type platform (**right**).

The conceived HWWES provides to the coupling of an SB or TLP platform with a WEC composed by a circular float to which eight arms are connected:

1. Four curved arms anchored by two 2D joints on one side to the SB or TLP platform and on the other to the upper part of the circular float. In the lower part of the arms are connected, in turn, four large hydraulic cylinders, which by means of two 2D joints are hooked on one side to the SB or TLP platform in a fixed manner and on the other with a mobile joint (sliding) to the lower part of the arms (Figure 2).

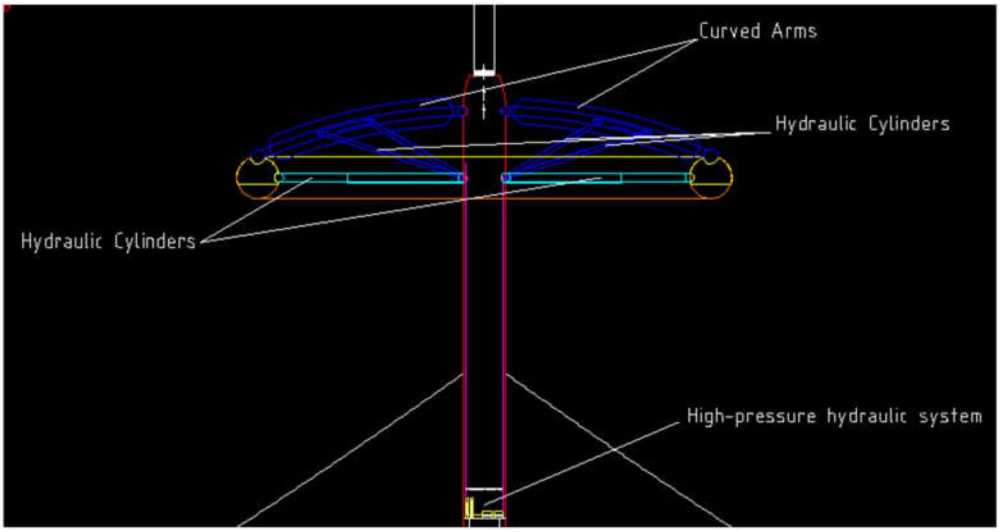

Figure 2. HWWES: WEC cross-section.

2. Four arms/large straight hydraulic cylinders anchored by two 2D joints on one side to the SB or TLP platform and, on the other, to the low internal part of the circular float (Figure 3).

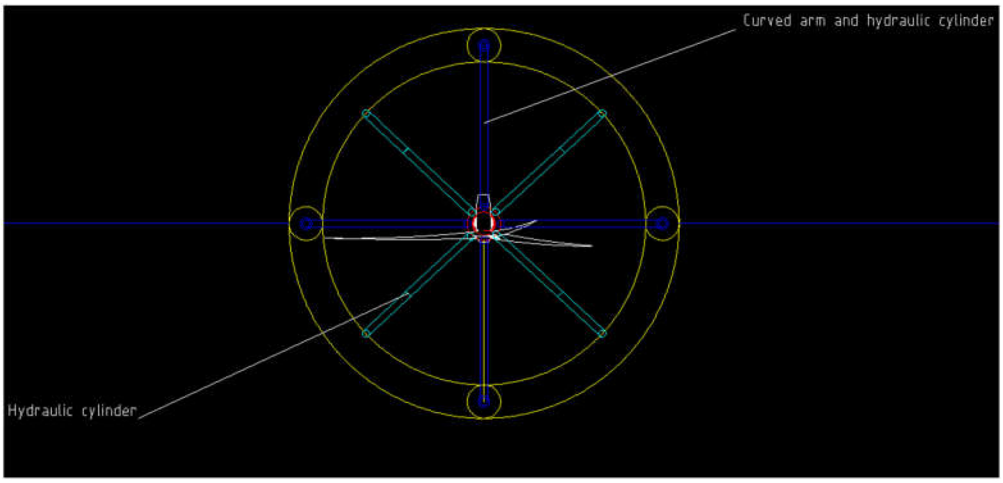

Figure 3. HWWES: WEC plan view.

A closed-circuit high-pressure hydraulic system is located in the low internal part of the platform in correspondence with the ballast in the case of platform SB; in the case of the TLP type platform, it is allocated in correspondence with the enlargement of the section in the submerged part.

The closed-circuit high-pressure hydraulic system is composed of:

- A closed circuit where the water inside is at high pressure
- A hydropneumatic accumulator
- A hyperbaric chamber
- A Pelton-type hydroelectric turbine
- A current generator

The eight hydraulic cylinders described above are connected to the closed-circuit; the alternative movement induced by the waves on the circular float activates the hydraulic cylinders, which through the closed-circuit, inject the water retained at high pressure by the hydropneumatic accumulator and by the hyperbaric chamber. This system releases a pressurized flow that turns the hydroelectric turbine, which, in turn, activates the generator that produces electricity.

A resistance check applied by hydraulic cylinders maximizes power generation when the waves are small and minimizes system response in the event of storms to avoid damage to the system. The system is equipped with end-of-stroke dampers, and it is foreseen to totally block the system in survival conditions when certain values of the damping coefficient (B_{pto}) and the spring coefficient (K_{pto}) are exceeded.

This HWWES is a first conceptual idea at an early stage of development and requires future studies and research activities to assess the feasibility of the concept. However, for the aims of this study and for the LCC analysis, other studies present in the literature have been considered, in particular, those described in [30,47]. From these studies emerged that, for a hybrid platform similar to the one proposed, under normal operating conditions, there is additional damping at the mean water level due to the presence of the WEC, which significantly reduces the pitch motion amplitude. There is also a less surge and a greater stability of the wind turbine, with a reduction in tension at the moorings and an increase of 10%–15% in production. It should also be noted that using a hybrid system, there is no need for the floater, which in the case of WEC represents 90% of the mass, the mooring system is shared (7%–25% of the WEC CAPEX) as well as the power cable (14% of the WEC CAPEX).

The following table (Table 3) shows the main characteristics of WEC device.

Table 3. WEC structural characteristics.

WEC	Value	Unit
Floater internal diameter	15	m
Floater external diameter	25	m
Floater cross section diameter	10	m
Floater cross section area	78.5	m^2
Floater volume	9860	m^3
Floater mass	470,397	kg
Weight anchoring	Increase of 10% of that of TLP or SB platform	kg
Weight mooring	Increase of 10% of that of TLP or SB platform	kg
B_{pto} operational	8000	kNs/m
B_{pto} survival	15,000	kNs/m
K_{pto} operational	50	kN/m
K_{pto} survival	100,000	kN/m

3. Method

IEC 60300-3-3: 2004 (https://webstore.iec.ch) proposed several models to calculate the life cost for a product. In the present study, the reference was the approach that considered the different phases of the process in accordance with the CBS model proposed by Fabrycky and Blanchard (1991) [33]. According to this model, the total cost of a product or system was calculated considering the costs of each of the main phases, and next, each cost was sub-divided into relevant incremental costs [33].

This model comprised of all the basic essential features of a holistic methodology to analyze the life cycle as well as determine the total cost of any product, and it may be implemented to address a wide variety of problems at different stages of the system product life cycle [48].

According to the CBS model [33] in the study presented here for the offshore wind/wave energy, the works described in [32,38,39] have been used as a guideline. The total life cycle cost of the system was decomposed into the costs of each of the main phases of the process [32,38,39]: Definition cost (C1), design cost (C2), manufacturing cost (C3), installation cost (C4), exploitation cost (C5), dismantling cost (C6).

$$LCC = C1 + C2 + C3 + C4 + C5 + C6 \quad (1)$$

Each of these costs has been divided into the corresponding secondary costs and analyzed separately (Figure 4).

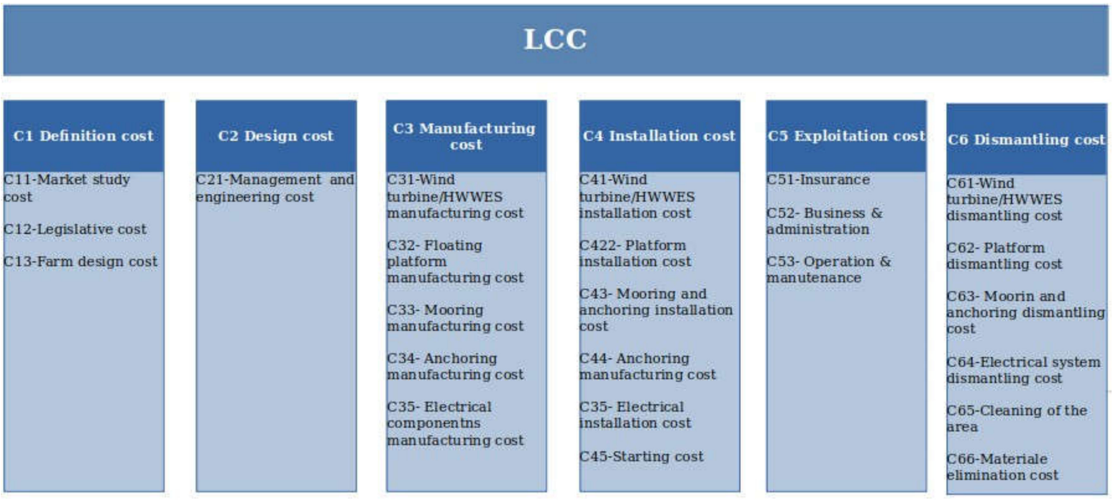

Figure 4. Main phases of the process for the life-cycle cost (LCC) analysis and related sub-costs.

■ Definition phase

The definition phase concerns the preliminary studies for the realization of an energy farm, and there are 3 related sub-costs [32,38]:

- C11—Market study cost
- C12—Legislative factors cost
- C13—Farm design cost

This cost is expressed as:

$$C1 = C11 + C12 + C13 \tag{2}$$

where C11 is the cost of the preliminary feasibility study, C12 is related to the country's taxes, while C13 depends on the study cost related to energy resource availability, sea condition, and geotechnical characteristics of the seabed. In particular:

$$C11 = C_{fsb} \tag{3}$$

$$C12 = C_{Tax} \times N_{WT/HWWES} \tag{4}$$

$$C13 = C_{es} + C_{gs} \times N_{WT/HWWES} \times P_{WT/HWWES} \tag{5}$$

where C_{fsb} is the cost of the preliminary feasibility study, C_{Tax} expresses the country's taxes, C_{es} expresses the study cost related to energy resource availability and sea condition, C_{gs} is related to the study cost of the geotechnical characteristics of the seabed, while $N_{WT/HWWES}$ and $P_{WT/HWWES}$ are the number and the power of wind turbine WT or HWWES, respectively.

■ Design phase

This cost takes into account the costs of engineering and management of the farm, and it is composed by [32,38]:

- C21—Management and engineering cost

$$C2 = C21 = C_{eng} \times N_{WT/HWWES} \times P_{WT/HWWES} \tag{6}$$

where C_{eng} is a unit cost inherent the activities of this detailed engineering phase and takes into account aspects related to electric cables, substation, calculation of mass of mooring and anchoring, etc.

■ Manufacturing phase

The manufacturing phase concerns the production of each component of the farm, and it is composed of [32,38]:

- C31—Wind turbine/HWWES manufacturing
- C32—Floating platforms manufacturing
- C33—Mooring manufacturing
- C34—Anchoring manufacturing
- C35—Electrical component manufacturing

$$C3 = C31 + C32 + C33 + C34 + C35 \tag{7}$$

Regarding C31 it is expressed as:

$$C31 = C_{MW} \times N_{WT/HWWES} \times P_{WT/HWWES} \tag{8}$$

where C_{MW} is the cost of the generator.

The sub-cost C32 comprises 2 costs: The floating platform cost (including circular float for HWWES) and the substation floating platform:

$$C32 = C_{pla\text{-}gen} \times N_{WT/HWWES} + C_{substat} \times P_{substat} \tag{9}$$

where C_{pla_gen} is the manufacturing cost of the floating platforms for generators, $C_{substat}$ is the manufacturing cost related to the floating platform of the substation, and $P_{substat}$ is the number of floating platforms for the substation. These costs comprise the materials costs (C_{DM}), the direct labor cost (C_{DL}), the activity cost (C_A), and the industrial profit (B) and are related to the mass of the platform (m_p), to the surface of the platform (S), to the cost per hour of the direct labor (C_{mo}), and to the steel cost (C_{steel}).

Regarding sub-cost C33, it has been calculated considering the manufacturing costs of the mooring for the platform of WT/HWWES.

$$C33 = [(w_m \times l_m)\, C_m]\, N_{ml} \times N_{WT/HWWES} \tag{10}$$

where w_m is the mooring weight, l_m is the mooring length, C_m is the mooring cost per kg, and N_{ml} is the number of mooring lines for the platform.

The cost of anchoring manufacturing is similar to the previous one for the mooring, and it is expressed as:

$$C34 = w_a \times C_a \times N_{ml} \times N_{WT/HWWES} \tag{11}$$

where w_a is the mass of anchoring, C_a is the anchoring cost per kilogram, and N_{ml} is the number of mooring lines of each platform, $N_{WT/HWWES}$ is the number of wind turbine WT or HWWES.

Regarding C35, it is expressed as:

$$C35 = C351 + C352 \tag{12}$$

The *C351* sub-cost is related to the electrical cable cost. It depends on the number of generators $N_{WT/HWWES}$, on the number of electrical cables N_{cable}, from their length $L_{cable,}$ and diameter D_{cable}, and on the cost of the electric cable C_{cable}.

$$C351 = N_{WT/HWWES}\left(\sum_{1}^{N_{WT/HWWES}} L_{cable} \times D_{cable} \times C_{cable}\right) + N_{sub}\left(\sum_{1}^{N_{sub}} L_{cable} \times D_{cable} \times C_{cable}\right) \tag{13}$$

The C352 sub-cost depends on the trasformers number (N_T) and on their cost (C_T) on the cost of the switchgear (C_{sw}) and on a coefficient β, which takes into account the greater wear compared to onshore installations:

$$C352 = \beta \times N_T\,(C_T + C_{sw}) \tag{14}$$

- Installation phase

The installation phase concerns the costs related to the installation of each component of the farm and it is composed of [32,38]:

- C41—Wind turbine/HWWES installation cost
- C42—Platform installation cost
- C43—Mooring and anchoring installation cost
- C44—Electrical installation cost
- C45—Starting cost

It is expressed as:

$$C4 = C41 + C42 + C43 + C44 + C45 \tag{15}$$

Regarding C41, it is the cost of installing the generator, and it is related to the costs of the shipyard and/or port operations ($Cgen_{sh/po}$), to the transport costs ($Cgen_{trans}$), and to the installation cost ($Cgen_{inst}$), as shown below:

$$C41 = Cgen_{sh/po} + Cgen_{trans} + Cgen_{inst} \tag{16}$$

The sub-cost C42 is related to the cost of installing the floating platforms. It comprises the costs related to the shipyard and/or port operations ($Cfp_{sh/po}$), the transport costs (Cfp_{trans}), and the installation cost (Cfp_{inst}).

$$C42 = Cfp_{sh/po} + Cfp_{transport} + Cfp_{installation} \tag{17}$$

The cost *C43* is related to the mooring and anchoring installation. This cost depends on the cost of the ship (C_{maship}), to the cost of its labor direct (C_{maDL}), to the cost of pumps and divers (C_{mapd}), to the number of anchors (N_{anch}), the time for installation (T_{mainst}):

$$C43 = C_{maship} + C_{maDL} + C_{mapd}\left(\frac{N_{anch}}{T_{mainst}}\right) \tag{18}$$

The cost of installing the electric system, C44, is composed of the installation cost of the electric cable (C_{inst_cable}) and by the cost of substation installation (C_{inst_sub}):

$$C44 = C_{inst\_cable} + C_{inst\_sub} \tag{19}$$

Finally, the sub- cost C45 is related to the start-up cost:

$$C45 = C_{start\text{-}up} \tag{20}$$

- Exploitation phase

The cost of this phase is composed of three sub-costs [32,38]:

- C51—Insurance
- C52—Business and administration
- C53—Operation and maintenance

$$C5 = C51 + C52 + C53 \tag{21}$$

The cost of insurance is defined as a percentage of the previous costs:

$$C51 = 0{,}01 \times (C1 + C2 + C3 + C4) \tag{22}$$

The business and administration cost C52 is related to the costs per year of the farm administration (C_{adm}) and of the legal aspects (C_{legal}) considering the life span of the farm (N_{yfarm})

$$C52 = N_{yfarm} \times (C_{adm} + C_{legal}) \tag{23}$$

The cost of operation and maintenance C53 depends on the preventive maintenance cost (C_{prev_maint}) and corrective cost (C_{corr}) for the entire life span of the farm:

$$C53 = N_{yfarm} \times (C_{prev\_maint} + C_{corr}) \tag{24}$$

- Dismantling phase

The dismantling phase is related to each activity of repowering or cleaning the area of installation of the farm at the end of its life span. This phase involves the dismantling of generators, platforms, mooring, anchoring, and electrical system, but also the cleaning of the area and elimination of all the materials. Dismantling involves transport and uninstalling the components. Some materials can be sold, which leads to a reduction in costs. The dismantling phase is composed of [32,38]:

- C61—Wind turbine/HWWEs dismantling cost
- C62—Platform dismantling cost
- C63—Mooring and anchoring dismantling cost
- C64—Electrical system dismantling cost
- C65—Cleaning of the area
- C66—Materials elimination cost

$$C6 = C61 + C62 + C63 + C64 + C65 + C66 \tag{25}$$

The sub-cost C61 is related to the generator dismantling cost ($C_{dism\_WT/HWWES}$), to the transport cost ($C_{dism\_tras\_WT/HWWES}$), and to the operations at port (C_{dism_op}).

$$C61 = C_{dism\_WT/HWWES} + C_{dism\_trans\_WT/HWWES} + C_{dism\_op} \tag{26}$$

The sub-cost C62 is related to the platform dismantling cost ($C_{dism\_plat\_WT/HWWES}$), to the transport cost ($C_{dism\_trans\_plat\_WT/HWWES}$), and to the operations at port ($C_{dism\_plat\_op}$):

$$C62 = C_{dism\_plat\_WT/HWWES} + C_{dism\_trans\_plat\_WT/HWWES} + C_{dism\_plat\_op} \tag{27}$$

The cost *C63* is related to the mooring and anchoring dismantling. This cost depends on the cost of the ship (C_{maship}), to the cost of its labor direct (C_{maDL}), to the cost of pumps and divers (C_{mapd}), to the number of anchors (N_{anch}), the time for dismantling ($T_{dismant}$):

$$C63 = C_{maship} + C_{maDL} + C_{mapd}\left(\frac{N_{anch}}{T_{dismant}}\right) \tag{28}$$

The cost C64, is composed of the dismantling cost of the electric cable ($C_{dismant\_cable}$) and by the cost of substation dismantling ($C_{dismant\_sub}$):

$$C64 = C_{dismant\_cable} + C_{dismant\_sub} \quad (29)$$

The sub-cost C65 is related to the cleaning area of the farm. It is related to the cost of cleaning the farm installation area (C_{area}), to the number of electrical cables (N_{cable}), to the number of diameters per line (N_{Dline}), to the diameter of the generator ($D_{WT/HWWES}$), the number of ($N_{WT/HWWES}$), and the number of diameters between WT/HWWES, ($ND_{WT/HWWES}$):

$$C65 = C_{area} \text{ x } (N_{cable} \times N_{dline} \times D_{WT/HWWES})(N_{WT/HWWES} \times ND_{WT/HWWES}) \quad (30)$$

The last sub-cost C66 depends to the cost of processing disposal materials ($C_{proc\_disp\text{-}mat}$), to the transportation cost ($C_{transp\_disp\_mat}$) and to elimination cost (C_{elim}):

$$C66 = C_{proc\_disp\text{-}mat} + C_{proc\_disp\text{-}mat} + C_{elim} \quad (31)$$

In addition to the LCC evaluation, the Levelized Cost of Energy (LCOE) analysis has also been carried out. To calculate the LCOE, the following equation has been used [49]:

$$LCOE = \frac{\sum_{t=0}^{N_{yfarm}} \frac{LCC_t}{(1+r)^t}}{\sum_{t=0}^{N_{yfarm}} \frac{E_t}{(1+r)^t}} \quad (32)$$

where LCC is the total life cycle cost (M€), E is the energy produced by the farm (MWh/year) (without considering efficiency losses), r is the discount rate expressed as the weighted average cost of capital (%), N_{yfarm} is the operational life span (years), and t is the individual year of lifetime. The cost expressed at the numerator varies according to the year; for the year 0, only the investment costs are considered, in the other years, the exploitation cost is considered, with the exception of the last year, which also includes the cost of dismantling. The life span N_{yfarm} is 25 years. The LCOE analysis has been performed considering 2 different values of r in accordance with the scenarios and projections provided by [50,51]. In particular, the values considered were 8% and 5% for a median scenario in 2030.

Regarding the HWWES, the uncertainty of the cost analysis was related to the fact that it was a first conceptual idea and to the difficulty in acquiring information of hybrid systems due to the few data and studies present in literature. However, a study considered useful and comparable for the purposes of the LCC analysis carried out in this work, was that described by Castro-Santos et al. (2016) [38]. This study referred to the Pelamis prototype, which, compared with the proposed WEC device, was based on the same operating principle and presents different parts in common. In particular, Pelamis was a semi-submerged “snake-like” offshore device and extracted energy from the wave motion. The device used in [38] was the Pelamis P2, a 2 s-generation machine, and it was composed of 5 sections connected by 4 flexible joints, anchored by only one end. Pelamis P2 was 180 m long, 4 m in diameter, and approximately 1350 tons in weight with a power output of 750 kW. Within each node, 4 hydraulic cylinders were allocated, connected by a closed hydraulic system to a hyperbaric chamber, to a hydraulic turbine and to a generator. This device, therefore, represented a WEC system similar to that proposed in this paper. In total, the Pelamis’ structure was composed of 4 nodes with a total of 16 hydraulic cylinders, 4 closed hydraulic systems, 4 hyperbaric chambers, 4 hydraulic turbines, and 4 generators. The proposed WEC device consisted, instead, of 8 hydraulic cylinders, 1 closed hydraulic system, 1 hyperbaric chamber, 1 hydraulic turbine, 1 generator, with a similar weight of about 1350 tons and a hypothetical power output of 350 kW.

4. Case Study Area

As previously mentioned, the LCC analysis has been carried out considering four study cases, two FOWFs, and two HWWFs.

The area chosen for the installation of the energy farms is off the port of Brindisi, region Apulia, Southern Italy, at different sea depths. For the farms with the TLP platform, the depth of installation is at 50 m, while for farms with the SB platform, the depth of installation is 150 m. The port of Brindisi has been chosen as a reference port for the logistic activities of installation, maintenance, and dismantling. The reference shipyard is in Ancona, in the region of Marche, Italy. Although Ancona is about 500 km away and is the one closest to the study area.

The parameter necessary for the LCC analysis has been acquired, considering the characteristic of the site, literature studies, and projects with similarities. Information and data of the installation site have been acquired by [52–55]. The following figure (Figure 5) shows the case study area.

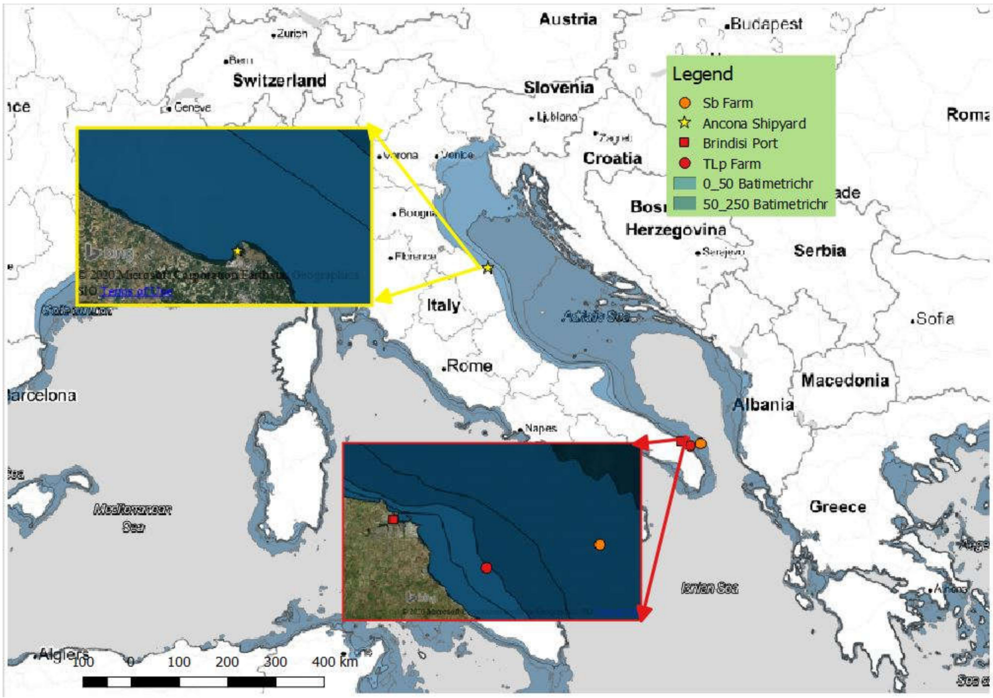

Figure 5. Case study area.

Furthermore, for the LCC analysis, other studies present in the literature have been considered, in particular those described in [30,47].

Regarding wind energy, offshore wind production has been evaluated considering the studies carried out by authors in [43,56]. The annual production of electrical energy has been assessed by using the histogram of the statistical frequency of occurrence of wind speed and the curve of the electric power produced by the wind turbine selected. Apulia region is characterized by values of annual average wind speed of about 6 m/s. Considering different depth categories and the two different floating type platforms, the annual producibility of a single turbine has been evaluated as equal to about 6302 MWh/year for the TLP platform and about 6926 MWh/year for the SB platform.

Regarding the wave energy, according to [57], the Adriatic Sea is characterized by the value of mean wave power equal to about 2 kW/m. The wave energy potential offshore for the Italian coasts has been estimated considering the three-hourly wave data set collected by the Italian Wave Buoys Network (IWN) since 1989. For the Apulian Region, the IWN buoy is placed offshore Monopoli (Bari), not far from Brindisi. In a successive study carried out by [58], the mean wave power offshore Apulian coasts estimated in the Italian Atlas has been integrated with the analysis of wave data measured by other two wave buoys placed offshore Tremiti Islands and Taranto. According to this study, the Apulian seas are characterized by values of average wave power, which is highly influenced by seasonal variability of waves characteristics with the summer months characterized by the lowest mean energy fluxes; offshore Monopoli the mean wave power is approximately equal to 1 kW/m. During winter, storms are more frequent and intense, and, consequently, an increase of wave power has been observed. Offshore Monopoli, the mean wave power exceeds 4 kW/m from December to February. Considering for the case study area, the mean wave power of about 2 KWh/m the annual energy production is about 210 Mwh/year.

5. Results and Discussion

For the case studies described in this paper, considering the methodology described in Section 3, the parameters necessary to calculate the cost of the entire life cycle of the energy farms have been derived by the information available, even if these are still limited, and on the basis of comparable studies present in the literature, considering different features of the devices and the location of the installation site.

The results obviously vary in relation to the type of platform considered both in the case of FOWT and in the case of HWWF. In the case of FOWF realized with the TLP platform, the total cost is 226.53 M€ (Table 4), while for FOWF with the SB platform, it is of 246.44 M€ (Table 5). The values follow the same trend also for HWWFs with a cost for the farm realized with the HWWES that combines the WEC with the TLP platform equal to 257.35 M€ (Table 6) and a cost of 280.07 M€ for the farm realized with the HWWES that combines the WEC and SB platform, respectively (Table 7).

Table 4. LCC analysis for floating offshore wind farm (FOWF) with the TLP platform.

LCC Analysis (TLP Floating Platform)			
Cost	Sub-cost	Value (M€)	Total (M€)
C1 Definition cost	C11—Market study cost	0.14	7.45
	C12—Legislative cost	0.22	
	C13—Farm design cost	7.09	
C2 Design cost	C21—Management and engineering cost	0.27	0.27
C3 Manufacturing cost	C31—Wind turbine manufacturing cost	43.41	78.48
	C32—Floating platform manufacturing cost	29.10	
	C33—Mooring manufacturing cost	2.91	
	C34—Anchoring manufacturing cost	0.35	
	C35—Electrical components manufacturing cost	2.72	
C4 Installation cost	C41—Wind turbine installation cost	0.64	64.45
	C42—Platform installation cost	52.45	
	C43—Mooring and anchoring installation cost	1.05	
	C44—Electrical installation cost	9.68	
	C45—Starting cost	0.61	
C5 Exploitation cost	C51—Insurance	1.46	37.61
	C52—Business and administration	0.83	
	C53—Operation and management	35.29	
C6 Dismantling cost	C61—Wind turbine dismantling cost	0.26	38.27
	C62—Platform dismantling cost	40.77	
	C63—Mooring and anchoring dismantling cost	0.58	
	C64—Electrical system dismantling cost	1.68	
	C65—Cleaning of the area	0.50	
	C66—Materials elimination cost	−5.52	
Total cost			226.53

Table 5. LCC analysis for FOWF with SB platform.

LCC Analysis (SB Floating Platform)			
Cost	Sub-cost	Value (M€)	Total (M€)
C1 Definition cost	C11–Market study cost	0.14	7.45
	C12–Legislative cost	0.22	
	C13–Farm design cost	7.09	
C2 Design cost	C21–Management and engineering cost	0.27	0.27
C3 Manufacturing cost	C31–Wind turbine manufacturing cost	78.80	142.46
	C32–Floating platform manufacturing cost	52.83	
	C33–Mooring manufacturing cost	5.27	
	C34–Anchoring manufacturing cost	0.63	
	C35–Electrical components manufacturing cost	4.93	
C4 Installation cost	C41–Wind turbine installation cost	0.31	31.03
	C42–Platform installation cost	25.25	
	C43–Mooring and anchoring installation cost	0.51	
	C44–Electrical installation cost	4.66	
	C45–Starting cost	0.30	
C5 Exploitation cost	C51–Insurance	1.8	65.13
	C52–Business and administration	1.46	
	C53–Operation and management	61.87	
C6 Dismantling cost	C61–Wind turbine dismantling cost	0.001	0.10
	C62–Platform dismantling cost	0.103	
	C63–Mooring and anchoring dismantling cost	0.001	
	C64–Electrical system dismantling cost	0.004	
	C65–Cleaning of the area	0.00	
	C66–Materials elimination cost	−0.014	
Total cost			246.44

Table 6. LCC analysis for HWWF (WEC and TLP platform).

LCC Analysis (WEC and TLP Platform)			
Cost	Sub-cost	Value (M€)	Total (M€)
C1 Definition cost	C11—Market study cost	0.14	7.45
	C12—Legislative cost	0.22	
	C13—Farm design cost	7.09	
C2 Design cost	C21—Management and engineering cost	0.28	0.28
C3 Manufacturing cost	C31—Wind turbine manufacturing cost	49.51	103.38
	C32—Floating platform manufacturing cost	47.30	
	C33—Mooring manufacturing cost	3.20	
	C34—Anchoring manufacturing cost	0.38	
	C35—Electrical components manufacturing cost	2.99	
C4 Installation cost	C41—Wind turbine installation cost	0.67	66.16
	C42—Platform installation cost	53.01	
	C43—Mooring and anchoring installation cost	1.15	
	C44—Electrical installation cost	10.64	
	C45—Starting cost	0.67	

Table 6. *Cont.*

LCC Analysis (WEC and TLP Platform)			
C5 Exploitation cost	C51—Insurance	1.77	41.50
	C52—Business and administration	0.91	
	C53—Operation and management	38.81	
C6 Dismantling cost	C61—Wind turbine dismantling cost	0.28	38.58
	C62—Platform dismantling cost	41.34	
	C63—Mooring and anchoring dismantling cost	0.63	
	C64—Electrical system dismantling cost	1.85	
	C65—Cleaning of the area	0.55	
	C66—Materials elimination cost	−6.07	
Total cost			257.35

Table 7. LCC analysis for HWWF (WEC and SB platform).

LCC Analysis (WEC and SB Platform)			
Cost	**Sub-cost**	**Value (M€)**	**Total (M€)**
C1 Definition cost	C11—Market study cost	0.14	7.45
	C12—Legislative cost	0.22	
	C13—Farm design cost	7.09	
C2 Design cost	C21—Management and engineering cost	0.28	0.28
C3 Manufacturing cost	C31—Wind turbine manufacturing cost	84.90	167.84
	C32—Floating platform manufacturing cost	71.03	
	C33—Mooring manufacturing cost	5.80	
	C34—Anchoring manufacturing cost	0.70	
	C35—Electrical components manufacturing cost	5.42	
C4 Installation cost	C41—Wind turbine installation cost	0.34	32.16
	C42—Platform installation cost	25.81	
	C43—Mooring and anchoring installation cost	0.56	
	C44—Electrical installation cost	5.13	
	C45—Starting cost	0.33	
C5 Exploitation cost	C51—Insurance	1.99	71.65
	C52—Business and administration	1.60	
	C53—Operation and management	68.06	
C6 Dismantling cost	C61—Wind turbine dismantling cost	0.02	0.69
	C62—Platform dismantling cost	0.67	
	C63—Mooring and anchoring dismantling cost	0.002	
	C64—Electrical system dismantling cost	0.005	
	C65—Cleaning of the area	0.001	
	C66—Materials elimination cost	−0.015	
Total cost			280.07

It is a highlight that the results of LCC analysis for the two HWWFs described in Table 6 and in Table 7 are already inclusive of the reduction in costs due to the sharing with the platforms for floating wind turbines.

Figure 6 shows the percentage distribution of the costs for the two FOWFs and for for the two HWWFs.

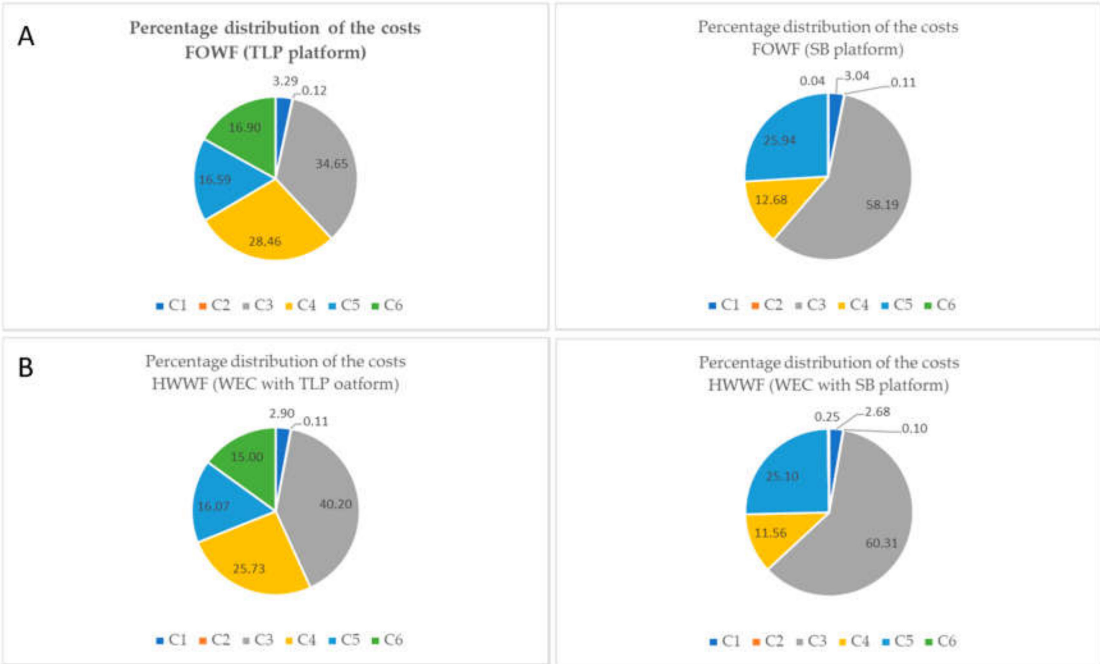

Figure 6. Percentage distribution of the costs for the two FOWFs (**A**) and for for the two HWWFs (**B**).

In general, it can be observed that the sub-costs that mostly affect the total are C3 (manufacturing cost), C4 (installation cost), C5 (exploitation cost), both in the case of FOWF and HWWF.

It can be highlighted that sub-costs C3 and C5 are higher in the case of installations with the SB platform; this can be attributed to several factors, including the installation depth and the greater distance from the shipyard and port, which are greater than the TLP installation. The greater depth of installation affects mooring and anchoring costs, while the greater distance from the shipyard and port affects, for example, the preventive and corrective maintenance.

Regarding HWWFs, the total cost is obviously higher than that of the FOWF, and the greater cost increase concerns the sub-cost C3 while the increase in the other sub-costs is less significant due to the sharing of anchoring, moorings, electricity infrastructures, costs of maintenance, etc. Regarding instead the percentage distribution of cost, as shown in Figure 6, there is a percentage increase in the sub-cost C3 while there is a percentage decrease for all the other sub-costs except for sub-cost C6 (dismantling cost) in the case of HWWF with SB platform (+0,21%). This is due to the greater distance from the shipyard and port, which affects the cost of eliminating the material, which is generally a revenue cost, which not to cover the other items of C6.

Regarding the LCOE results, considering the first scenario, the following values have been obtained: For FOWF considering the TLP platform, the value is 334 €/MWh, for the FOWF with the SB platform, the value is 404 €/MWh, for the HWWF with TLP platform the value is 412 €/MWh while for HWWF with SB platform the value is 446 €/Mwh. For a median scenario in 2030, the values obtained are the following: For FOWF considering the TLP platform, the value is 269 €/MWh, for the FOWF with the SB platform, the value is 319 €/MWh, for the HWWF with TLP platform the value is 330 €/MWh while for HWWF with the SB platform, the value is 352 €/MWh.

The capacity factor, expressed as the ratio between the average power generated and the nominal power produced, is around 15% for FWT and 22% for the HWWES.

Regarding the first scenario, the LCOE values obtained appear to be high, making the realization of the farms not very economically feasible; instead, the results obtained for the second scenario are more comparable with the ranges obtained according to the studies and the perspectives described in [59]. In particular, according to [59], the LCOE range value for offshore wind energy production for Western Europe is between 126 €/MWh and 314 €/MWh; regarding the wave energy, the low and central outlook scenarios refer to values of 284 €/MWh and 496 €/MWh, respectively. Considering that the Western Europe area is characterized by greater wind and wave availability compared to the central Mediterranean area, the results can be considered comparable. Instead, compared with the values for FOWF reported in [50], the obtained values are higher.

The values obtained from the economic analysis presented in this paper are also to be framed in the context of the small size of the farms and turbine considered, which have not favored the economics of scale. Furthermore, the high distance of the shipyard from the farm installation area should also be considered, which negatively affecting the overall costs. Regarding the HWWES, the low availability of wave energy had a negative impact on electricity production. However, it should be noted that for these farms, the cost increase compared to the FOWF has not been excessively high; this suggests a possible greater economic feasibility in areas with higher wave energy availability.

Finally, it should also be noted that currently, reference costs are based on real project data from operational offshore installations in shallow waters. In the coming years, pre-commercial and commercial-scale projects for floating offshore installation should help to establish more firmly the cost of a floating foundation [50], thus allowing more accurate economic assessments. Furthermore, in the next few years, technological innovation, the decrease of many cost items, and together with the expected reduction of the discount rate [50], could make the installation of such farms more competitive and feasible.

6. Conclusions

In the present work, an LCC and LCOE analysis for two FOWFs and two HWWFs has been carried out. The aim of the work has been to carry out a preliminary economic analysis for renewable energy farms in the Mediterranean area; this area, characterized by deep waters, is becoming of growing interest for floating offshore energy production considering the technological advancements of wind and wave structures. The obtained results allow for highlighting the different cost items for the two types of energy farms and two types of platforms considered. The analysis has also been performed in relation to the percentage distribution of the costs. Therefore, the study has individuated the different cost items that mostly affect the total cost, favoring considerations and assessments on these aspects for the improvement of the considered energy farms.

Regarding the hybrid farm, it has been realized by considering a hybrid system proposal with reference to a new concept. Research on National, European, and Global patent databases have shown that there are currently few similar concepts. Furthermore, numerical studies on a similar system show positive results in terms of technological feasibility. Therefore, the study has been carried out considering this system, although with the awareness that future further developments are needed to assess its real feasibility. For HWWFs, it emerged that for this type of farm, almost all cost items do not present significant cost increase compared to FOWF, due to the sharing of different components of the farm, and has been quantified by the percentage distribution. The installation sites are in the Apulia region in southern Italy, which is a region that is investing a lot in renewable energy like offshore wind energy. For this region, for the aim of investment prospects in this sector, the study highlighted the usefulness for this region to having a shipyard that would significantly reduce manufacturing, installation maintenance, and disposal costs.

The results of the LCOE analysis show high values, which must also be framed in the context of the energy availability of the study area, the size of the farm, and the distance of the shipyard. The economic analysis has been carried out aware that a more realistic approach for the realization of these farms requires successive studies aimed at evaluating the real energy production together with site-specific analysis. For the two types of farms, these studies will also have to consider the possible effects of climate change on energy production considering the various studies that are being carried out in the Mediterranean area in relation to future projections of climate change at a regional and global scale.

In the next years, the forecasts of cost and discount rate reductions, and the technological advance of the sector, could make the realization of these types of energy farms more feasible and economically more competitive.

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Abbreviations

LCC	Life-Cycle Cost
CBS	Cost Breakdown Structure
FOWF	Floating offshore wind farm
HWWF	Hybrid wind-wave farm
HWWES	Hybrid wind-wave energy system
WEC	Wave energy converter
TLP	Tension Leg Platform
SB	Spar Buoy platform
LCOE	Levelized Cost of Energy
SS	Semi-Submersible platform
FWT	Floating wind turbine
B_{pto}	Damping coefficient
K_{pto}	Spring coefficient
$N_{WT/HWWES}$	Number of wind turbine/Number of hybrid wind-wave energy system
$P_{WT/HWWES}$	Power of wind turbine/Power of hybrid wind-wave energy system
C_{fsb}	Cost of the preliminary feasibility study
C_{Tax}	Country's taxes
C_{es}	Study cost related to energy resource availability and sea condition
C_{gs}	Study cost of the geotechnical characteristics of the seabed
C_{eng}	Unit cost of engineering phase
C_{MW}	Cost of generator
C_{pla_gen}	Manufacturing cost of the floating platforms for generators
$C_{substat}$	Manufacturing cost related to the floating platform of the substation
$P_{substat}$	Number of floating platforms for the substation
C_{DM}	Material costs
C_{DL}	Direct labor cost
C_A	Activity cost
B	Industrial profit
m_p	Platform mass
S	Surface of the platforms
C_{mo}	Direct labor cost per hour
C_{steel}	Steel cost
w_m	Moorings weight
l_m	Moorings length
C_m	Mooring cost per Kg
N_{ml}	Number of mooring lines for platform
N_{cable}	Number of electrical cables
L_{cable}	Length of electrical cables

D_{cable}	Diameter of electrical cables
C_{cable}	Cost in €/m of the electric cable
β	Correction coefficient
N_T	Number transformer
C_T	Cost of transformer
C_{sw}	Cost of witchgear
$Cgen_{sh/po}$	Costs installation generator related to shipyard and/or port operations
$Cgen_{trans}$	Transport costs for generator installation
$Cgen_{inst}$	Costs installation generator
$Cfp_{sh/po}$	Costs installation platforms related to shipyard and/or port operations
Cfp_{trans}	Transport costs for installation floating platforms
Cfp_{inst}	Costs installation of floating platforms
C_{maship}	Ship costs for mooring and anchor installation
C_{maDL}	Labor direct for mooring and anchor installation
C_{mapd}	Cost of pumps and divers for mooring and anchor installation
N_{anch}	Number of anchors
T_{mainst}	Time for mooring and anchoring installation
C_{inst_cable}	Costs of installation of the electrical cables
C_{inst_sub}	Cost installing the substation
$C_{start\text{-}up}$	Cost start-up
N_{yfarm}	Number of years of the life-cycle of the farm
C_{adm}	Costs administration farm
C_{legal}	Costs legal aspects
C_{prev_maint}	Preventive maintenance cost
C_{corr}	Corrective cost
$C_{dism\_WT/HWWES}$	Generator dismantling cost
$C_{dism\_tras\_WT/HWWES}$	Transport cost (generator dismantling)
C_{dism_op}	Operations at port (generator dismantling)
$C_{dism\_plat\_WT/HWWES}$	Platform dismantling cost
$C_{dism\_trans\_plat\_WT/HWWES}$	Transport cost (platform dismantling)
$C_{dism\_plat\_op}$	Operations at port (platform dismantling)
C_{maship}	Cost of the ship
C_{mapd}	Pump and diverse costs
$T_{dismant}$	Time for dismantling
C_{area}	Cost of cleaning the farm area
N_{dline}	Number of diameters for lines
$D_{WT/HWWES}$	Generator diameter
$ND_{WT/HWWES}$	Number of diameters between WT/HWWES,
$C_{proc\_disp\text{-}mat}$	Cost of processing disposal materials
$C_{transp\_disp\_mat}$	Transportation cost (disposal materials)
C_{elim}	Elimination cost
E	Energy production (Mwh/year)
r	Discount rate (%)

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