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Cost Assessment Methodology and Economic Viability of Tidal Energy Projects

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Abstract: The exploitation of technologies with which to harness the energy from ocean currents will have considerable possibilities in the future thanks to their enormous potential for electricity production and their high predictability. In this respect, the development of methodologies for the economic viability of these technologies is fundamental to the attainment of a consistent quantification of their costs and the discovery of their economic viability, while simultaneously attracting investment in these technologies. This paper presents a methodology with which to determine the economic viability of tidal energy projects, which includes a technical study of the life-cycle costs into which the development of a tidal farm can be decomposed: concept and definition, design and development, manufacturing, installation, operation and maintenance and dismantling. These cost structures are additionally subdivided by considering their sub-costs and bearing in mind the main components of the tidal farm: the nacelle, the supporting tidal energy converter structure and the export power system. Furthermore, a technical study is developed in order to obtain an estimation of the annual energy produced (and, consequently, the incomes generated if the electric tariff is known) by considering its principal attributes: the characteristics of the current, the ability of the device to capture energy and its ability to convert and export the energy. The methodology has been applied (together with a sensibility analysis) to the particular case of a farm composed of first generation tidal energy converters in one of the Channel Island Races, the Alderney Race, in the U.K., and the results have been attained by means of the computation of engineering indexes, such as the net present value, the internal rate of return, the discounted payback period and the levelized cost of energy, which indicate that the proposed project is economically viable for all the case studies.

Keywords: renewable energy; marine currents; tidal energy; economic viability; cost assessment; life-cycle costs

1. Introduction

There has been, in recent years, an increasing concern about global climate change, the importance of reducing greenhouse gas emissions, the current dependency on and limited life span of fossil fuels and the current increase in energy prices [1–3]. Renewable energies play a key role in this framework, and this has been recognized by the European Union (EU), which in 2009 established the need to reduce 20% of energy consumption and 20% of carbon dioxide (CO_2) emissions with the objective of 20% of the EU's final energy consumption originating from renewable sources in 2020 [4,5]. This milestone was a definite boost as regards the promotion of clean renewable technologies for electricity generation. It led to the fixing of legally-binding targets that marked a path for the future, with continuity beyond 2020, and opened up a horizon of opportunities for the development of new sources and renewable technologies, as well as economic sectors linked to renewable energies.

It is, therefore, necessary to attain and increase the aforementioned renewable energy percentages in the near future, and there is consequently a growing interest in the contribution of other types of renewable energy that are currently less developed and will remain so for the next five years, since their technologies are still in the development and demonstration phases [6–8]. One of these is ocean energy whose exploitation could provide the following opportunities and benefits [9–11]: energy independence, decarbonization, job creation and being a complement to other renewable sources within the global energy mix (improved predictability, decreased variability, spatial concentration and socio-economic benefits) [12,13].

This research is focused on tidal energy, which, although its technologies are at the prototype and pre-commercial demonstration at sea phases, will have considerable possibilities in the future thanks to its enormous potential for electricity production and its high predictability [14–16]. In this respect, any system based on renewable sources that is intended for commercialization must first pass through an economic assessment in order to achieve a consistent quantification of the costs of these technologies, to verify the profitability of the system while simultaneously attracting investment and to allow commercialization [17]. However, limited experience hinders the evaluation of tidal energy projects with an adequate level of confidence owing to the current lack of data and the high level of uncertainty [18]. We should note that, despite the potential benefits of this renewable energy source, very few studies have focused specifically on the economic feasibility of these systems and how to estimate them. Issues such as costs [19], the net present value [20] (NPV), the internal rate of return (IRR) [21], the discounted payback-period (DPBP) [22], the levelized cost of energy (LCOE) [23] or the life-cycle costs (LCC)—from an economical [24] or an environmental [25] point of view, among others—have been developed in previous works that were principally focused on other products/process and other sorts of renewable energy sources [26]. With regard to tidal energy projects, several authors have performed studies for tidal farms, indicating the general percentages of influences of each cost, but without providing a specific methodology with which to calculate the cost involved in a tidal farm [27,28]. A more detailed description of the development of the economic viability of marine energy farms is found in [29], which includes interesting information regarding how to obtain the annual energy produced (AEP) and to determine the costs of the main components of a marine energy farm. However, with regard to the AEP, this research does not include information about aspects such as the stele effect, blend effect, velocity deficit or effects related to the tidal farm topology, among others, which have a great influence on the determination of the final value of the AEP. Furthermore, with regard to the determination of the costs of the main components of the tidal farm, the aforementioned research does not provide detailed information with which to compute detailed aspects of the costs of the main sub-components of which the tidal farm is composed (turbine, foundation, export energy system), and this influences the final value of the cost incurred by the energy farm during its service life. Under these premises, and with the intention of covering this lack, the main contributions to the state of the art of this research are the following: (i) a methodology with which to determine the economic viability of tidal energy projects and that includes a technical study of the LCC, defined by modifying the recommendations proposed in [30], since this normative is focused on a product rather than a process. Bearing in mind the aforementioned consideration, the main stages into which the development of a tidal farm can be decomposed are: concept and definition, design and development, manufacturing, installation, operation and maintenance (O&M) and dismantling. These cost structures are additionally subdivided by considering their sub-costs and bearing in mind the main components of the tidal farm: the nacelle, the supporting tidal energy converter (TEC) structure and the export power system. Specific expressions have been included in order to increase the detail involved in calculating the LCC for tidal energy projects, which is rarely found in other studies. A technical study is then performed in order to describe the estimation of the AEP in detail (and, consequently, the incomes generated if the electric tariff is known) by considering its principal attributes: the characteristics of the current, the ability of the device to capture energy and its ability to convert and export the energy. Additionally, (ii) the proposed methodology has been used to discover the economic viability of a tidal farm located in one of the Channel Island Races, the Alderney Race, in the U.K. A sensitivity analysis was also carried out. The results obtained through the use of engineering indexes such as NPV, IRR, DPBP and LCOE indicate that the project is economically feasible for all the case studies. Finally, the remainder of the paper is structured as follows: Section 2 illustrates the proposed methodology for the economic evaluation of tidal energy projects. Section 3 shows a case case study of a 50-MW tidal farm in the Alderney Race. Section 4 depicts the numerical results obtained for the case study, and finally, Section 5 shows our conclusions and proposals for future works.

2. Proposed Methodology of the Evaluation of Tidal Energy Projects

The methodology proposed for the economic feasibility of these energy projects is based on the LCC of the project and the determination of the AEP. The aim of attaining the LCC is to provide useful criteria for decision-making at any or all of the stages that comprise the life-cycle of the project. In essence, the LCC represents an accounting structure that contains mathematical expressions with which to estimate the associated costs of a project during its service life [31,32]. We should emphasize that the development of a methodology for the economic assessment of projects based on LCC is a simplified representation of the real world based on the main characteristics and relations of the project and their corresponding estimation costs. In order to carry out an adequate LCC for tidal energy projects from the perspective of environmentally sustainable economic efficiency, it is fundamental to understand the life-cycle of this sort of project and the activities to be performed at all the stages. All the decisions made as regards the design, manufacture, operation, maintenance, and so on, including environmental impact, may therefore affect the total cost in a substantial manner [33,34]. The stages of which the proposed methodology are composed are the following (See Figure 1): (i) concept and definition costs: C_1; (ii) design and development costs: C_2; (iii) manufacturing costs: C_3; (iv) installation costs: C_4; (v) operation and maintenance costs: C_5; and (vi) decommissioning costs: C_6. Once these costs have been computed, the total LCC of a tidal energy project yields the following result:

$$LCC_{TEP} = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \quad (1)$$

Furthermore, the information concerning the site (water depth, tidal energy resource, weather windows, distance from shore, etc.), the device (geometry, configuration, power, materials, etc.) and the export energy system (farm topology, connectors, cables, transformation platform, converters, etc.) makes it possible to estimate the AEP and, consequently, the incomes obtained from the possible commercial exploitation of the tidal energy project. All the aforementioned information is then analyzed by means of several indicators (NPV, IRR, DPBP and LCOE) that will have a decisive influence on the decision to invest in the tidal energy project and will allow comparative studies with other renewable energy sources to take place. It is important to note that the estimated costs and the estimation of the AEP included in the methodology for the economic feasibility of tidal energy projects have been obtained by studying the current scientific literature, internal technical reports generated at the Escuela Técnica Superior de Ingenieros Navales of the Universidad Politécnica de Madrid and information provided by companies that specialize in tidal energy projects and shipyards. The following subsections deal with all the details required to describe the proposed methodology.

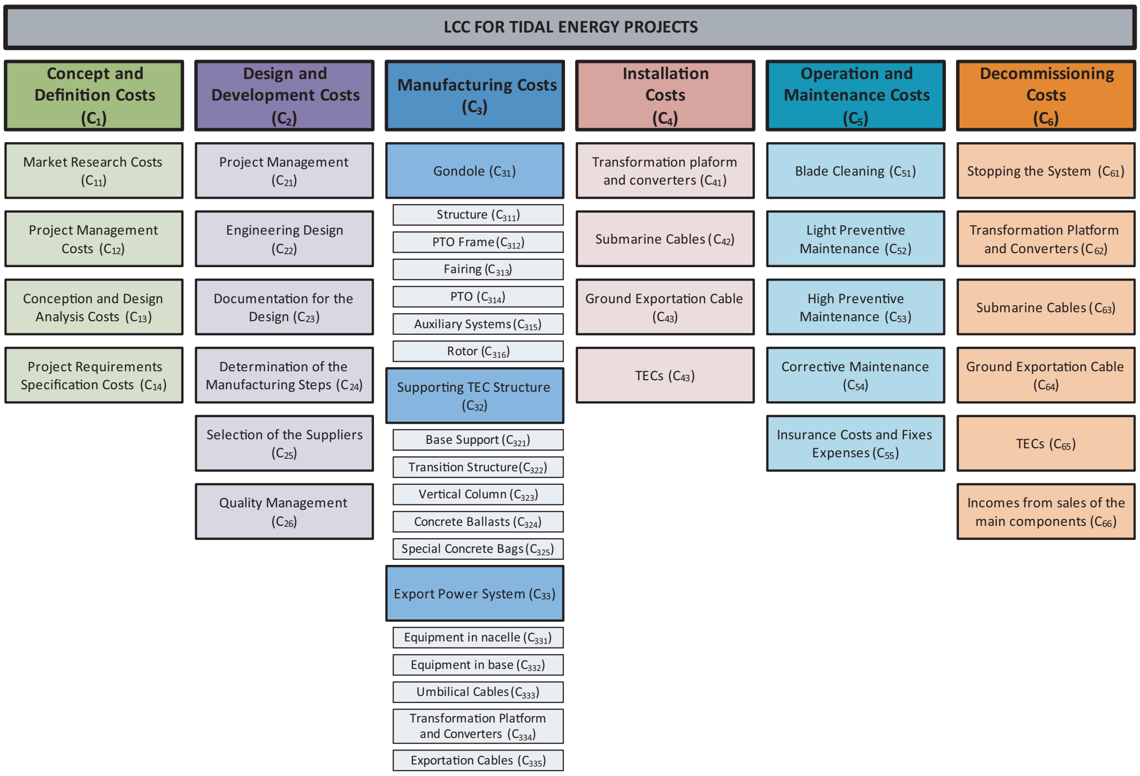

Figure 1. Cost and sub-costs for the proposed methodology. LCC, life-cycle costs; TEC, tidal energy converter.

2.1. Concept and Definition Costs (C_1)

The concept and definition costs are attributed to various activities whose objective is to guarantee the project's viability. If we focus on tidal energy projects, the following costs are typically included:

- Market research costs (C_{11}): It is necessary to determine the current state of the market as regards tidal energy generation and to analyze the economic viability of the tidal energy project on the basis of environmental information, site information (water depth, tidal energy resource, weather windows, distance from shore, etc.), device information (geometry, configuration, power, materials, etc.), export power system information (farm topology, connectors, cables, transformation platform, converters, etc.), and so on. This cost is modeled as a constant value, i.e.,

$$C_{11} = C_{MR} \tag{2}$$

  where C_{MR} is defined as a constant value.
- Project management costs (C_{12}): These include the completion and obtaining of certificates and regulations, such as environmental studies (seabed surveys, local species and ecosystem surveys, coastal process surveys, etc.), social impact surveys and the authorization of the installation. These costs are usually constant, with the exception of the authorization of the installation of the tidal farm, which depends on the surface required to install the tidal energy project. These costs are, therefore, modeled as:

$$C_{12} = C_{CS} + C_{AI} \cdot S_{TEP} \tag{3}$$

  where C_{CS} denotes a constant value in €, C_{AI} expresses the cost per m^2 in €/m^2 and S_{TEP} defines the surface required to install the tidal energy project in m^2.
- Conception of the tidal farm and design analysis costs (C_{13}): This comprises the cost of obtaining the preliminary solution for the tidal energy project. One or more possible solutions are

synthesized at this stage and are then evaluated with regard to the restrictions imposed. This cost is modeled as a constant value, i.e.,

$$C_{13} = C_{CDA} \tag{4}$$

where C_{CDA} denotes a constant value in €.

- Project requirements' specification costs (C_{14}): At this stage, the main components of the tidal energy project and their interactions are determined in sufficient detail to be able to carry out an objective evaluation of the project proposal. In the particular case of tidal farms, it is necessary to consider site information (water depth, tidal energy resource, weather windows, distance from shore, etc.), device information (geometry, configuration, power, materials, etc.), export power system information (farm topology, connectors, cables, transformation platform, converters, etc.), and so on. This cost is again modeled as a constant value, i.e.,

$$C_{14} = C_{PRS} \tag{5}$$

where C_{PRS} expresses a constant value in €.

Once these costs have been attained, the concept and definition costs, C_1, are obtained as follows:

$$C_1 = C_{11} + C_{12} + C_{13} + C_{14} \tag{6}$$

2.2. Design and Development Costs (C_2)

The design and development costs are those related to fulfilling the specification of the project requirements and providing proofs of its compliance. They typically include costs regarding: (i) project management (C_{21}); (ii) engineering design (C_{22}), the inclusion of reliability, maintainability and activities for environmental protection; (iii) detailed documentation for the design (C_{23}); (iv) determining the manufacturing steps required for the park (C_{24}); (v) the selection of the suppliers (C_{25}); or (vi) quality management (C_{26}). All these costs can be modeled as a constant value, i.e.,

$$C_2 = C_{21} + C_{22} + C_{23} + C_{24} + C_{25} + C_{26} = C_{DD} \tag{7}$$

where C_{DD} defines a constant value in €.

2.3. Manufacturing Costs (C_3)

The manufacturing costs comprise all the costs involved in manufacturing the elements from which the tidal farm will be constructed. In the case of tidal energy projects, the main costs considered at this stage are the following:

- Nacelle (C_{31}): This cost (see Figure 2) is estimated by considering the following sub-costs associated with the structure of the nacelle (C_{311}): power take off (PTO) frame (C_{312}), fairing (C_{313}), PTO (C_{314}), auxiliary systems (C_{315}) and rotor (C_{316}). They are estimated as follows:
  - Structure of the nacelle (C_{311}): This cost is estimated by considering the number of TECs manufactured, N_M, the cost per kg of the carbon steel produced, C_{SD}, in €/kg, and the mass of the structure (front cover, horizontal and vertical cylinders, longitudinal and transversal reinforcements, etc.) of the nacelle, m_{SD}, in kg, i.e.,

$$C_{311} = N_M \cdot m_{SD} \cdot C_{SD} \tag{8}$$

  - PTO frame (C_{312}): This cost is estimated by considering the number of TECs manufactured, the cost per kg of the carbon steel produced for this element, C_{PTOF}, in €/kg, and the mass of this element, m_{PTOF}, in kg, i.e.,

$$C_{312} = N_M \cdot m_{PTOF} \cdot C_{PTOF} \tag{9}$$

– Fairing (C_{313}): This cost is estimated by considering the number of TECs manufactured, the cost per kg of the fiberglass produced for this element, C_F, in €/kg, and the mass of this element, m_F, in kg, i.e.,

$$C_{313} = N_M \cdot m_F \cdot C_F \tag{10}$$

– PTO (C_{314}): This cost considers the number of TECs manufactured and the costs of the thrust bearing, the gearbox, the high-speed shaft, the slip ring system, the brake system, the electrical generator, etc., of each TEC [35–38]. The main variables required to estimate these costs are included in a nonlinear function depending on the number of TECs manufactured, the power of each TEC, P_T, the cost per MW of the thrust bearing, C_{TB}, in €/MW, the cost per MW of the high-speed shaft, C_{HSS}, in €/MW, the cost per MW of the gearbox, C_G, in €/MW, the cost per MW of the brake system, C_{BS}, in €/MW, and the cost per MW of the electrical generator, C_{EG}, in €/MW, i.e.,

$$C_{314} = N_M \cdot \left(P_T \cdot (C_{TB} + C_{BS} + C_{HSS} + C_{EG}) + P_T^{1.2} \cdot C_G\right) \tag{11}$$

– Auxiliary systems (C_{315}): This cost considers the number of TECs manufactured and the costs of the yaw system, cooling system, pressure oil system, protection and connection switches, bilge system, compressed air system, circuit board, control system, condition monitoring systems and added elements. The main variables required to estimate this cost are the number of TECs manufactured, the power of each TEC, the mass of the yaw system, m_{YS}, in kg, the cost per kg for this element, C_{YS}, in €/kg, the cost per MW of the cooling system, C_{COS}, in €/MW, the cost per MW of the pressure oil system, C_{POS}, in €/MW, the mass of the protection and connection switches m_{SWT} in kg, the cost per kg of these elements, C_{SWT}, in €/kg, the mass of the bilge system m_{BIS} in kg, the cost per kg of this element, C_{BIS}, in €/kg, the mass of the compressed air system m_{ACS} in kg, the cost per kg of this element, C_{ACS}, in €/kg, the mass of the circuit board m_{CB} in kg, the cost per kg of this element, C_{CB}, in €/kg, the mass of the control system m_{CTS} in kg, the cost per kg of these elements, C_{CTS}, in €/kg, the cost per MW of the condition monitoring system, C_{CMS}, in €/MW, the mass of the added elements m_{AE} in kg, and the cost per kg of this element, C_{AE}, in €/kg, i.e.,

$$\begin{aligned} C_{315} = \quad & N_M \cdot (m_{YS} \cdot C_{YS} + m_{CTS} \cdot C_{CTS} + P_T\,(C_{COS} + C_{POS} + C_{CMS}) + \\ & m_{SWT} \cdot C_{SWT} + m_{BIS} \cdot C_{BIS} + m_{ACS} \cdot C_{ACS} + m_{CB} \cdot C_{CB} + \\ & m_{AE} \cdot C_{AE}) \end{aligned} \tag{12}$$

– Rotor (C_{316}): This cost is estimated by considering the number of TECs manufactured, the costs of the blades, the pitch system and the core of the rotor. The main variables required to estimate these costs are included in a nonlinear function depending on the number of TECs manufactured, the radius of the rotor, R_R, in m, the cost per m of each blade, C_B, in €/m, the number of blades per TEC, N_B, the cost per m of the pitch system, C_{PS}, in €/m, the cost per m of the low-speed shaft, C_{LSS} in €/m, and the cost per m of the core of the rotor, C_{CR}, in €/m, i.e.,

$$C_{316} = N_M \cdot \left(N_B \cdot R_R^{2.7} \cdot C_B + R_R \cdot (C_{PS} + C_{LSS} + C_{CR})\right) \tag{13}$$

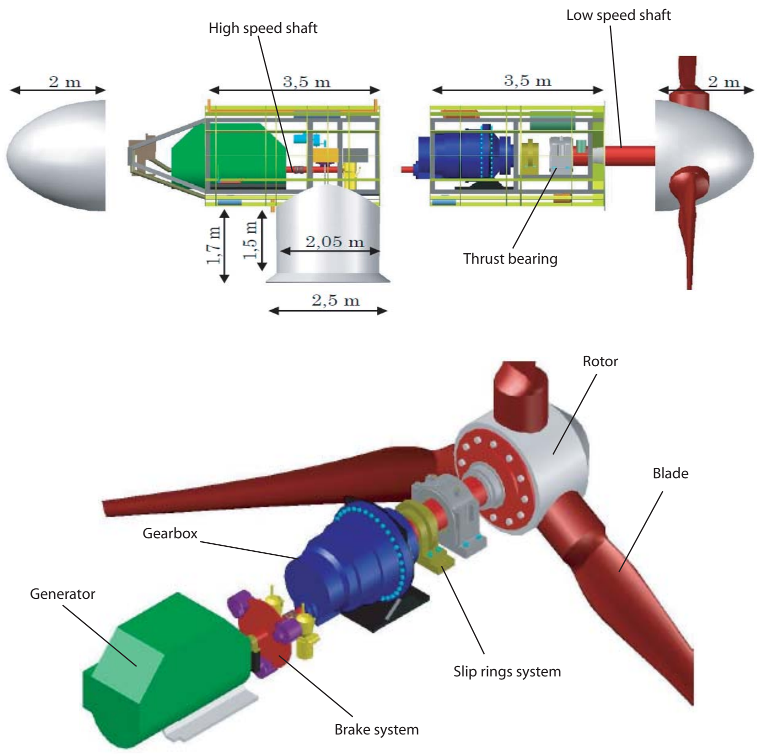

Figure 2. Distribution of the main elements within the nacelle.

- Supporting TEC structure (C_{32}): This cost is estimated by considering the following sub-costs (see Figure 3) associated with the base support (C_{321}), the transition structure (C_{322}), the vertical column (C_{323}), the concrete ballasts (C_{324}) and the special concrete bags (C_{325}). They are estimated as follows:

  – Base support (C_{321}): This cost is estimated by considering the number of TECs installed, N_I, the cost per kg of the steel produced, C_{TBS}, in €/kg, and the mass of the structure, m_{TBS}, in kg, i.e.,

$$C_{321} = N_I \cdot m_{TBS} \cdot C_{TBS} \tag{14}$$

  – Transition structure (C_{322}): This cost is estimated by considering the number of TECs installed, the cost per kg of the steel produced, C_{TTS}, in €/kg, and the mass of the structure, m_{TTS}, in kg, i.e.,

$$C_{322} = N_I \cdot m_{TTS} \cdot C_{TTS} \tag{15}$$

  – Vertical column (C_{323}): This cost is estimated by considering the number of TECs installed, the cost per kg of the steel produced, C_{TVC}, in €/kg, and the mass of the structure, m_{TVC}, in kg, i.e.,

$$C_{323} = N_I \cdot m_{TVC} \cdot C_{TVC} \tag{16}$$

  – Concrete ballasts (C_{324}): This cost is estimated by considering the number of TECs installed, the amount of concrete ballast per TEC, N_{CB}, the cost per kg of the concrete produced, C_{EC}, in €/kg, and the mass of the ballast, m_{EC}, in kg, i.e.,

$$C_{324} = N_I \cdot N_{CB} \cdot m_{EC} \cdot C_{EC} \tag{17}$$

  – Special concrete bags (C_{325}): This cost is estimated by considering the number of TECs installed, the amount of special concrete bags per TEC, N_{BG}, the cost per kg of the concrete contained in the special bags, C_{BG}, in €/kg, and the mass of the concrete produced for the special bags, m_{BG}, in kg, i.e.,

$$C_{325} = N_I \cdot N_{BG} \cdot m_{BG} \cdot C_{BG} \tag{18}$$

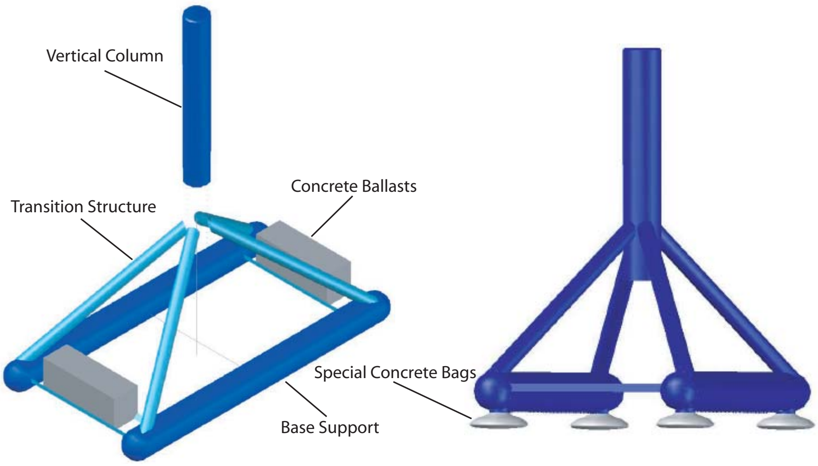

Figure 3. Supporting TEC structure.

- Export power system (C_{33}): This cost is estimated by considering the following sub-costs associated with the electrical equipment in the nacelle (C_{331}), the electrical equipment in the base support (C_{332}), the umbilical cables (C_{333}), the transformation platform and the converters (C_{334}) and the exportation cable (C_{335}). They are estimated as follows:

  – Electrical equipment in the nacelle (C_{331}): This cost is estimated by considering the number of TECs manufactured, the power of each TEC, the cost per MW of the protection switch, C_{PSW}, in €/MW, the mass of the submarine connector, m_{SC}, in kg, and the cost per kg of this element, C_{SC}, in €/kg, i.e.,

  $$C_{331} = N_M \cdot (P_T \cdot C_{PSW} + m_{SC} \cdot C_{SC}) \tag{19}$$

  – Electrical equipment in the base support (C_{332}): This cost is estimated by considering the number of TECs installed, the mass of the submarine connector installed in the base, m_{BSC}, in kg, the cost per kg of this element, C_{BSC}, in €/kg, the mass of the internal wiring, m_{IW}, in kg, the cost per kg of this element, C_{IW}, in €/kg, the mass of the connection box, m_{CBX}, in kg and the cost per kg of this element, C_{CBX}, in €/kg, i.e.,

  $$C_{332} = N_I \cdot (m_{BSC} \cdot C_{BSC} + m_{IW} \cdot C_{IW} + m_{CBX} \cdot C_{CBX}) \tag{20}$$

  – Umbilical cables (C_{333}): This cost is estimated by considering the length of the umbilical cables, L_{UC}, in m, and the cost per m of this element, C_{UC}, in €/m, i.e.,

  $$C_{333} = L_{UC} \cdot C_{UC} \tag{21}$$

  – Transformation platform and converters (C_{334}): This cost is estimated by considering the number of TECs installed, the power of each TEC, the cost per MW of the rectifiers, C_R, in €/MW, the cost per MW of the inverters, C_I, in €/MW, the cost per MW of the electrical boxes, C_{EB}, in €/MW, the number of transformers, N_{TF}, the cost per MW of the transformers,

C_{TF}, in €/MW, the mass of the transformation platform, m_{TP}, in kg, and the cost per kg of this element, C_{TP}, in €/kg, i.e.,

$$C_{334} = N_I \cdot P_T \cdot (C_R + C_I + C_{EB} + N_{TF} \cdot C_{TF}) + m_{TP} \cdot C_{TP} \tag{22}$$

– Exportation cables (C_{335}): This cost is estimated by considering the number of submarine exportation cables, N_{SEC}, the length of the submarine exportation cables, L_{SEC}, in m, the cost per m of this element, C_{SEC}, in €/m, the length of the ground exportation cables, L_{GEC}, in m, and the cost per m of this element, C_{GEC}, in €/m, i.e.,

$$C_{335} = N_{SEC} \cdot L_{SEC} \cdot C_{SEC} + L_{GEC} \cdot C_{GEC} \tag{23}$$

Once these costs have been attained, the manufacturing costs, C_3, are obtained as follows:

$$C_3 = C_{31} + C_{32} + C_{33} \tag{24}$$

2.4. Installation Costs (C_4)

The estimation of the installation costs for tidal farms is of particular difficulty owing to the characteristics and uncertainties of the offshore operations and the volatility costs of the vessels used in these operations. Several concepts need to be considered if these costs are to be estimated in an appropriate manner:

- Specialized vessels: The evolution of offshore wind farms and the development of advanced offshore technologies result in progressions in infrastructure and the attainment of specific solutions for these particular sectors. When designing the installation and O&M procedures, it is therefore essential to search for specialized vessels with which to perform these activities. Without the existence of these specialized vessels, the costs of these operations would be so high that the economic viability of these offshore systems might be seriously compromised.
- Base port: When studying of the implementation of a tidal farm, it is very important to determine the location of nearby industrial base ports. These ports need to be equipped with sufficient means for the reception of materials and components and have the capabilities to load and upload these materials and components, along with the means to perform TEC maintenance tasks. The location of the port base has a great influence as regards ensuring a reduction in the installation and O&M costs.
- Weather windows: Weather phenomena, such as wind velocity, wave height and tidal current velocity, need to be studied in order to perform the installation and the O&M procedures in safe conditions. The definition of favorable weather windows throughout the different seasons of the year is fundamental if an adequate and a safe planning of the installation and the O&M tasks is to take place.

Bearing the previous considerations of the cost structure in mind, the following costs are considered at this stage:

- Installation of the transformation platform and converters (C_{41}): In order to evaluate this activity, it is necessary to include the cost of leasing the vessels (specialized installation vessel, cable-laying vessel, remotely-operated vehicles (ROVs), etc.), $C_{V_{IPC}}$, the cost of technical labor (technical specialist, divers, etc.), $C_{TL_{IPC}}$, the cost of operations in the port (excavators, winches, trucks, etc), $C_{PO_{IPC}}$, which depend on the distance from the tidal farm to the base port, d_{P-TF}, and the weather windows, WW; i.e.,

$$C_{41} = C_{V_{IPC}}\,(d_{P-TF}, WW) + C_{TL_{IPC}}\,(d_{P-TF}, WW) + C_{PO_{IPC}}\,(d_{P-TF}, WW) \tag{25}$$

- Installation of the submarine cables (C_{42}): This cost has a similar structure to that explained previously. In order to estimate this activity, it is necessary to include the cost of leasing the vessels, $C_{V_{ISC}}$, the cost of technical labor, $C_{TL_{ISC}}$, the cost of operations in the port, $C_{PO_{ISC}}$, which depend on the distance from the tidal farm to the base port, and the weather windows; i.e.,

$$C_{42} = C_{V_{ISC}}\,(d_{P-TF}, WW) + C_{TL_{ISC}}\,(d_{P-TF}, WW) + C_{PO_{ISC}}\,(d_{P-TF}, WW) \tag{26}$$

- Installation of the ground exportation cable (C_{43}): In order to evaluate this activity, it is again necessary to include the cost of leasing the vessels, $C_{V_{IGEC}}$, the cost of technical labor, $C_{TL_{IGEC}}$, the cost of operations in the port, $C_{PO_{IGEC}}$, which depend on the distance from the tidal farm to the base port, and weather windows:

$$C_{43} = C_{V_{IGEC}}\,(d_{P-TF}, WW) + C_{TL_{IGEC}}\,(d_{P-TF}, WW) + C_{PO_{IGEC}}\,(d_{P-TF}, WW) \tag{27}$$

- Installation of the TECs (C_{44}): Finally, and using a similar procedure to that described above, the evaluation of this cost structure is the following (cost of leasing the vessels, $C_{V_{ITEC}}$, the cost of technical labor, $C_{TL_{ITEC}}$, the cost of operations in the port, $C_{PO_{ITEC}}$, which depend on the distance from the tidal farm to the base port, and weather windows):

$$C_{44} = C_{V_{ITEC}}\,(d_{P-TF}, WW) + C_{TL_{ITEC}}\,(d_{P-TF}, WW) + C_{PO_{ITEC}}\,(d_{P-TF}, WW) \tag{28}$$

Once these costs have been attained, the installation costs, C_4, are obtained as follows:

$$C_4 = C_{41} + C_{42} + C_{43} + C_{44}. \tag{29}$$

2.5. Operation and Maintenance Costs (C_5)

In the case of tidal energy projects, O&M procedures suppose an important part of the design of the TECs and will have a direct and important repercussion as regards the time it takes to get the TECs working properly and, consequently, the energy generation capacity of the tidal farm. The reduction in the time spent on these tasks substantially influences the reduction in the cost of energy [39]. Additionally, and as explained in the previous section, the performance of the maintenance tasks should be carried out in periods of small tidal currents in order to ensure safe conditions when raising the nacelle and carrying out insertion operations on it and to minimize energy losses during the time spent on these operations [40]. During the development of an effective maintenance plan for the tidal farm (and the cost structure), it is necessary to estimate the downtimes that each component requires, the failure probability of each component, the specialized vessels used in these tasks and the weather windows in which these tasks can be performed [41,42]. Furthermore, it is very important to include the insurance costs and fixed expenses in the operation and maintenance cost structure, because they are some of the most expensive factors in the offshore renewable energy sector [17]. The computation of this cost structure has been performed in accordance with the procedures developed in [43,44]. Bearing the previous considerations regarding the cost structure in mind, the following costs are considered at this stage:

- Blade cleaning (C_{51}): This concerns the removal of algae, microorganisms and fouling from the blades of the TEC. This cost depends on the number of TECs manufactured, the downtimes spent on this process, D_{BC}, the weather windows, the transport costs, C_{TBC}, the labor costs, C_{LBC}, and the costs incurred as the result of production losses, C_{PLBC}, i.e.,

$$C_{51} = N_M \cdot (C_{TBC}\,(D_{BC}, WW) + C_{LBC}\,(D_{BC}, WW) + C_{PLBC}\,(D_{BC}, WW)) \tag{30}$$

- Light preventive maintenance (C_{52}): This involves light general maintenance (grease changes, review of painting defects, etc.) in the TECs (nacelle + supporting structure) and the export energy system. The estimation of this cost category is carried out by considering the number of TECs manufactured, the downtimes spent on this process, D_{LPM}, the weather windows, WW, the transport costs, C_{TLPM}, the labor costs, C_{LLPM}, the material costs, C_{MLPM}, and the costs incurred as the result of production losses, C_{PLLPM}, i.e.,

$$\begin{aligned} C_{52} = \quad & N_M \cdot (C_{TLPM}\,(D_{LPM}, WW) + C_{LLPM}\,(D_{LPM}, WW) + \\ & C_{MLPM}\,(D_{LPM}, WW) + C_{PLLPM}\,(D_{LPM}, WW)) \end{aligned} \tag{31}$$

- High preventive maintenance (C_{53}): This implies more in-depth maintenance (bearing replacements, inspection of the nacelle and the structure components, etc.) in the TECs (nacelle + supporting structure) and the export energy system. As in the previous category, the estimation of this cost category is carried out by considering the number of TECs manufactured, the downtimes spent on this process, D_{HPM}, the weather windows, WW, the transport costs, C_{THPM}, the labor costs, C_{LHPM}, the material costs, C_{MHPM}, and the costs incurred as the result of production losses, C_{PLHPM}, i.e.,

$$\begin{aligned} C_{53} = \quad & N_M \cdot (C_{THPM}\,(D_{HPM}, WW) + C_{LHPM}\,(D_{HPM}, WW) + \\ & C_{MHPM}\,(D_{HPM}, WW) + C_{PLHPM}\,(D_{HPM}, WW)) \end{aligned} \tag{32}$$

- Corrective maintenance (C_{54}): This concerns repairing the TECs (nacelle + supporting structure) and the export energy system, The computation of this cost category is developed by including the number of TECs manufactured, the failure probability of the i-component of the tidal farm, P_{F_i}, the downtimes spent on this process, D_{CM}, the weather windows, WW, the transport costs, C_{TCM}, the labor costs, C_{LCM}, the material costs, C_{MCM}, and the costs incurred as the result of production losses, C_{PLCM}, i.e.,

$$\begin{aligned} C_{54} = \quad & N_M \cdot (C_{TCM}\,(D_{CM}, WW) + C_{LCM}\,(D_{CM}, WW) + \\ & C_{MCM}\,(D_{CM}, WW) + C_{PLCM}\,(D_{CM}, WW)) \end{aligned} \tag{33}$$

- Insurance costs and fixed expenses (C_{55}): The estimation of this cost is an area that needs to be studied in depth within the offshore renewable energy sector. According to the scientific literature, two possible metrics can be used to estimate these costs [17]: (a) % of the total capital expenditure (CAPEX, an expenditure whose benefit extends beyond one year; this concept will be explained in detail in Section 2.8); or (b) €/MWh. For example, in [45], the cost of insurance is estimated as 2% of the CAPEX, while [46] includes an estimation of the insurance cost of 15,000 €per MW. In our case, the insurance costs and fixed expenses have been estimated as a percentage of the CAPEX.

Once these costs have been attained, the operation and maintenance costs, C_5, are obtained as follows:

$$C_5 = C_{51} + C_{52} + C_{53} + C_{54} + C_{55}. \tag{34}$$

2.6. Decommissioning Costs (C_6)

This stage includes all the costs incurred during the removal and disposal of the project components and leaving the sea as it was initially. It is expected that this will occur in approximately 20 years [47]. The decommissioning costs incurred are typically the following: (i) stopping the system (C_{61}); (ii) dismantling the transformation platform and converters (C_{62}); (iii) dismantling the submarine cables (C_{63}); (iv) dismantling the exportation cable (C_{64}); (v) dismantling the TECs (C_{65}). At this stage, it is necessary to include the incomes obtained from the sales of the main components (steel, converters, etc.) of the tidal farm (C_{66}). This value will be modeled as a negative value in the cost structure. Once these costs have been attained, the decommissioning costs, C_6, are obtained as follows:

$$C_6 = C_{61} + C_{62} + C_{63} + C_{64} + C_{65} + C_{66}. \quad (35)$$

As occurred with the installation costs and the operation and maintenance costs, the estimation of the decommissioning costs for tidal farms is of particular difficulty owing to the characteristics and uncertainties of the offshore operations, the volatility costs of the vessels used in these operations, the weather windows, etc. Additionally, there is currently no accurate information about the quantification of the economic costs of offshore tidal farms owing to the fact that no offshore tidal farm has, as yet, been dismantled.

Another possible option is the renewal/total inspection of the devices and platforms in such a way that the service life of the tidal farm can be extended. This is a very interesting option because some of the investments made will barely need renewal. The cost of energy of the tidal farm during this elongated service life would, therefore, substantially decrease, thus making the project more profitable.

Bearing the aforementioned considerations and the uncertainties currently involved at this stage in mind, the dismantling cost will not be included in the case study performed.

2.7. Annual Energy Produced

One of the most important items, and a clear indicator for decision-making during the installation of a tidal farm, is the achievement of the AEP. In order to estimate the AEP (and consequently, the incomes generated if the electric tariff is known), it is necessary to determine a model that considers the characteristics of the current (speed, direction, distribution, etc.), the ability of the device to capture energy and its ability to convert and export energy. The following items are required to estimate the AEP (see Figure 4):

- Estimation of the current velocity at the depth of the rotor. During the computation of this parameter, it is necessary to consider the following aspects:
  - Histograms of the current velocity: These histograms provide information about the frequency (number of hours) with which a given current velocity is repeated in a year. They provide useful information as regards estimating the energy produced by a TEC [48].
  - Current profile at the operating depth: A relation of 1/7 is used to adapt the measured current velocities at the surface (represented in the aforementioned histograms) to the operating depth [49].

$$V_r = V_h \left(\frac{Z_r}{Z_h} \right)^{\frac{1}{7}} \quad (36)$$

    where V_r represents the rotor velocity in m/s, V_h denotes the velocity at the sea surface in m/s, Z_r is the rotor depth in m and Z_h expresses the depth of the water column.
  - Stele effect, blend effect and velocity deficit: When the flow passes through the rotor, it transfers energy to it, but it simultaneously undergoes diverse hydrodynamic phenomena that result in a flow speed deficit downstream of the rotor. It additionally generates a stele with a great turbulence that causes disturbances in the flow. This effect appears when the flow passes through each TEC and, consequently, when it passes each row of the tidal farm. The last rows of the tidal farms will, therefore, receive a lower quality flow, signifying that the TECs will capture less energy [50]. This is obtained by employing the following expression:

$$a = 1 - \sqrt{1 - C_t} \quad (37)$$

$$A_s = \left(\frac{1 - 0.5a}{1 - a} \right) A_r \quad (38)$$

$$V_s = (1 - a) V_r \quad (39)$$

where a is the stele coefficient, C_t represents the buoyancy coefficient, V_r denotes the input flow velocity in m/s, A_r is the surface of the rotor in m^2, V_s denotes the output flow velocity in m/s and A_s expresses the output flow surface in m^2. Once this effect has been estimated, it is necessary to take into account the blend effect between the perturbed flow and the free flow downstream of the rotor by considering the configuration of the tidal farm and applying the energy conservation law. The following result is obtained:

$$A_s V_s^2 + (A_t - A_r) V_r^2 = A_t V_z^2 \tag{40}$$

where A_t denotes the total frontal surface of the device and V_z expresses the final velocity of the blended flow in m/s. The velocity deficit is then computed as:

$$V_x = (V_s - V_z) e^{-0.2 \frac{x}{D}} \tag{41}$$

with an exponential decay model for an intermediate point (x, V_x) located between the rotor output (stele effect) and the blend flow downstream and where D denotes the diameter of the rotor [51]. The usual values of velocity deficit are around 5% when the flow passes through a row of TECs.

- Performance of the PTO: When the tidal current velocity is small, the PTO of the TEC is working in a partial regime that only captures a part of its nominal power, and its performance is, therefore, considerably reduced. This effect needs to be considered in order to estimate a realistic value of the AEP and to characterize the cut-in velocity (the cut-in velocity of a TEC can be defined as the minimum velocity required to generate energy with which to feed at least the auxiliary systems that allow the TEC to operate) of the device.
- Additional requirements when estimating the total energy produced: Several requirements need to be considered when estimating a realistic value of the total energy:
  - Availability factor: The TEC does not always work properly owing to device breakdowns and maintenance periods. This availability factor needs to be estimated on the basis of the information obtained from the maintenance procedures used, weather windows, and so on.
  - Tidal farm topology: This influences the final value of the AEP, and it is necessary to evaluate the performance of each TEC on the basis of the position (row, column) that it occupies within the tidal farm.
  - Performance of the power export system: The last stage involved in obtaining the AEP for the tidal farm is its exportation and conversion into quality energy. The performance of the export power system from the generators of the TECs to the water-to-wire point therefore needs to be included.

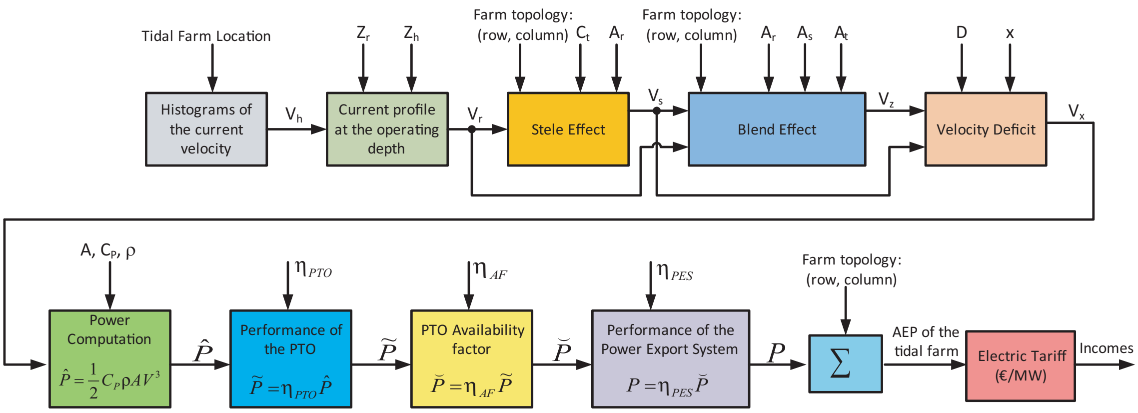

Figure 4. Summary of the computation of the annual energy produced (AEP).

2.8. Viability Analysis

After computing the LCC and the AEP of the project, it is necessary to perform a feasibility analysis, which is done by studying several economic and technical indicators. The conclusions obtained from this study will have a decisive influence on the decision-making process, showing the current value of the benefits, the profitability of the project and the possibility of performing comparative studies with other renewable energy sources. Of the various economic and technical indicators, we include the following: (i) net present value (NPV); (ii) internal rate of return (IRR); (iii) discounted payback period (DPBP); and (iv) levelized cost of energy (LCOE). The NPV, IRR and DPBP are indicators that usually depend on market conditions. However, the LCOE is independent of market conditions and is frequently used in the study of renewable energy projects. The following subsections deal with the definition of these indicators.

2.8.1. Net Present Value

The NPV is represented by the difference between the present value of cash inflows (given by the total investment costs and the operational costs) and the present value of cash outflows (obtained from the cost of the electricity and the tidal resource) [52]. The NPV is usually used to analyze the profitability of a project or a projected investment. It is obtained by means of the following expression:

$$NPV = -C_0 + \sum_{t=1}^{n} C_t \cdot (1+k)^{-t} \tag{42}$$

where C_0 denotes the initial investment costs (€), C_t represents the net cash flow during the period t in years (€), k is the annual discount rate and n expresses the number of time periods.

2.8.2. Internal Rate of Return

The IRR is defined as the annual discount rate that makes the NPV of all net cash flows equal to zero [52]. It is also used to analyze the profitability of investing in the project. From a financial perspective, the IRR provides a measure of the gross annual relative profitability per monetary unit involved in the project. Mathematically, it is expressed as follows:

$$0 = -C_0 + \sum_{t=1}^{n} C_t \cdot (1+r)^{-t} \quad \Rightarrow \quad r = IRR \tag{43}$$

Owing to the nature of Expression (43), the IRR must be calculated by employing an iterative process or using programmed mathematical software.

2.8.3. Discounted Payback Period

The DPBP provides the number of years it takes to break even after the initial expenditure [52]. It is configured as a suitable method with which to evaluate risk investments that allows the profitability analysis performed with the NPV and the IRR to be carried out. It is obtained by means of the following expression:

$$DPBP = A + \frac{B}{C} \tag{44}$$

where A denotes the last year with a negative discounted cumulative cash flow, B represents the absolute value of discounted cumulative cash flow at the end of the year A and C is the discounted cash flow during the year after A.

2.8.4. Levelized Cost of Energy

The LCOE is a useful tool with which to compare the unit cost of different technologies throughout their economic life and serves as a benchmarking or ranking tool with which to compare different technological alternatives that could be achieved by different investments and time operations. It should be studied on the basis of specific countries (or even the same place) [53,54]. The LCOE is defined as the life-cycle cost divided by lifetime energy production and is computed as follows [55]:

$$LCOE = \frac{C_{CAPEX} + \sum_{t=1}^{n} C_{OPEX_t} \cdot (1+k)^{-t}}{\sum_{t=1}^{n} E_t \cdot (1+k)^{-t}} \tag{45}$$

where CAPEX (capital expenditure) signifies an expenditure whose benefit extends beyond one year. C_{CAPEX} mostly includes the general costs, the cost of the PTO and ancillary/mooring systems, the main support structure of the TEC, base and/or mooring, other device units, the installation of the TEC and other units, the TEC farm hub platform and the energy transportation systems, among others [38]. OPEX (operational expenditures) involves the ongoing cost of running the tidal energy project. C_{OPEX} includes administrative costs, scheduled and unscheduled O&M costs, insurance, taxes, rent payments and shipping and shore facilities. The C_{OPEX} values have a high uncertainty owing to the lack of precision and the lack of available published data and have a tendency to increase when equipment ages [56]. C_{CAPEX} denotes the capital expenditures in €; C_{OPEX_t} expresses the operating expenditures in year tin €; and E_t represents the production of energy in years texpressed in kWh.

3. Case Study in the Alderney Race

3.1. The Alderney Race

Alderney is one of the islands in the English Channel whose surface is almost 10 km^2 and is dependent on the British Crown. It is located approximately 18 km to the west of the Cape of La Hague (France), 37 km to the northwest of Guernsey and 110 km to the south of the English coast. The tidal farm is planned to be located in the orange square illustrated in Figure 5a. The strait in this place has a width of 13 km and a minimum depth of 17 m, while the proposed zones are 30–40 m in depth. The search for a relatively plain zone with the adequate depth is essential for the location of the tidal farm. Moreover, the seabed in this location is composed of large plates of hard flat rocks [57].

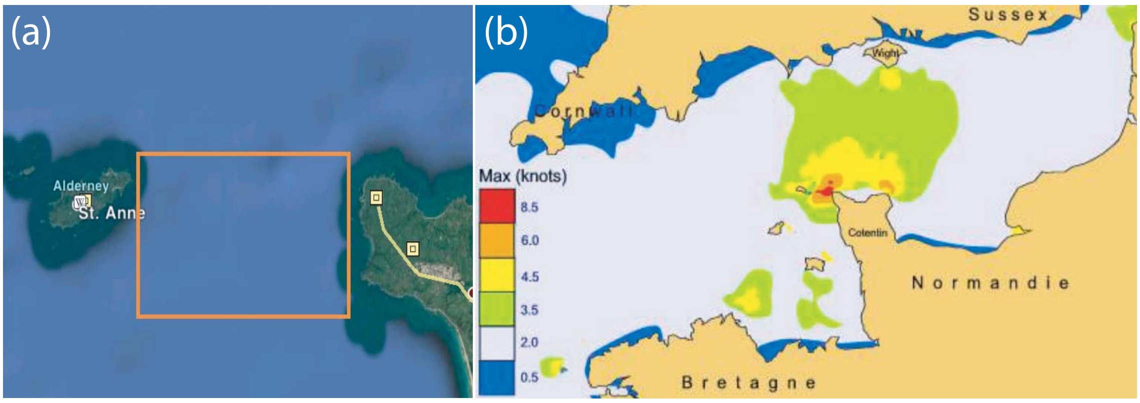

Figure 5. Alderney Race: (**a**) delimited zone for the tidal farm; (**b**) current velocity in the Alderney Race.

Furthermore, the marine currents in the Alderney Race can flow in both directions depending on the tide. This phenomenon is continuously repeated according to the period of the tides. What is more, the current velocity is almost always greater than 1 ms^{-1} (see Figure 5b), which will be translated into high electricity production for a high percentage of time. The information provided about the current velocities, distance to shore and the seabed compositions allowed us to conclude that this site is a very good candidate for the construction and commercial exploitation of a tidal farm.

3.2. Configuration of the Proposed First Generation Tidal Farm

The proposed tidal farm is composed of 42 TECs of 1.2 MW. The TECs selected have an open rotor configuration whose axis is parallel to the flow (see Figure 6). The nacelle of the TEC can be separated from the structure in order to facilitate the maintenance tasks, but when the nacelle is mounted on the structure, its orientation is fixed, thus making it mandatory for it to have a pitch controllable blade system so as to maximize the energy captured in both current directions. The diameter of the blades is 20 m, and the TEC is fixed to the seabed by gravity, i.e., the structure that supports the TEC is supported on the seabed by means of a substantial mass. Finally, the tidal farm will be composed of a small number of rows, with 11, 10, 11, 10 TECs per row, in order to minimize the shadow effect in the last rows and maximize the total energy captured by the tidal farm.

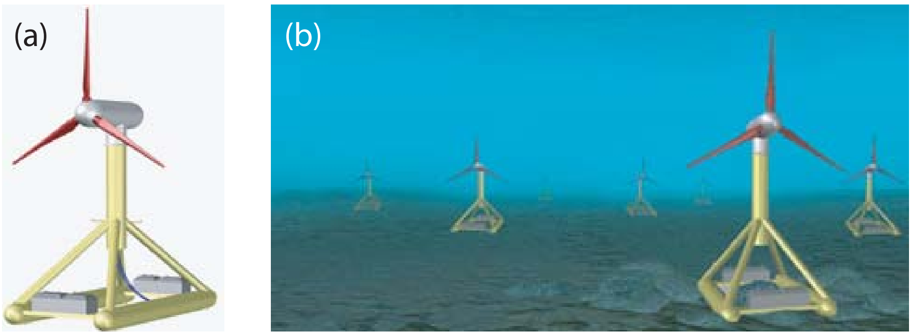

Figure 6. (**a**) Proposed TEC; (**b**) view of proposed tidal farm.

3.3. Installation Procedures

For the case study developed, the following considerations and installation procedures have been kept in mind for the tidal farm during its expected service life of 20 years [47]:

3.3.1. Previous Considerations

Bearing the assumptions made in Section 2 in mind, the following considerations have been included to develop the installation and the O&M costs:

- Vessels: We have selected the HF4 vessel designed by MojoMaritime® for this purpose. This vessel is characterized by its dynamic positioning and the fact that it is able to work under extreme conditions. The use of this vessel makes it possible to obtain larger weather windows for the development of the installation and O&M procedures and, consequently, helps substantially reduce the total life-cycle costs. An additional advantage of the vessel selected is that it allows the transportation of all the equipment required to install one TEC or the transportation of three nacelles at the same time (see Figure 7), which helps reduce the maintenance tasks.
- Base port: The port selected for its operative qualities is the Port of Cherburg in France. The distance from the base port to the location of the tidal farm is approximately 39 km. This distance, although small, cannot be ignored since, owing to the nominal velocity of the vessel selected (14 knots), it would spend 1.5 h on the displacements.
- Weather windows: Bearing the vessel characteristics and the climatological considerations in mind, we have obtained the percentages of time during which operations can be performed in each season. These are the following: (a) spring: 75% (68 days); (b) summer: 95% (87 days); (c) autumn: 50% (46 days); and (d) winter: 15% (14 days). These percentages show that it is possible to operate around 215 days a year, which is sufficient time to satisfy the installation and maintenance procedures of the tidal farm.

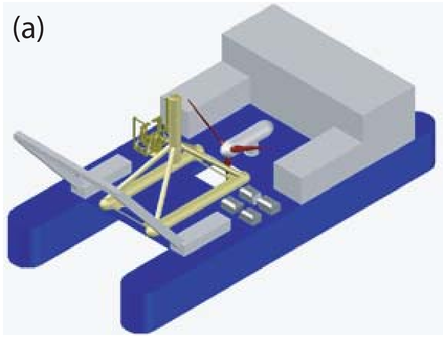

Figure 7. (**a**) HF4 installation vessel transporting the equipment needed to install the TEC; (**b**) HF4 installation vessel transporting nacelles.

3.3.2. Installation Sequence

After studying the seabed on which the tidal farm will be located, it is necessary to study the zones in which the TECs will be situated in order to find the optimal route for the cables that belong to the TECs and the umbilical cables that join the TECs to the transformation platform, as well as to define the optimal route for the exportation cable. Figure 8 illustrates an example of the installation procedure of the TECs.

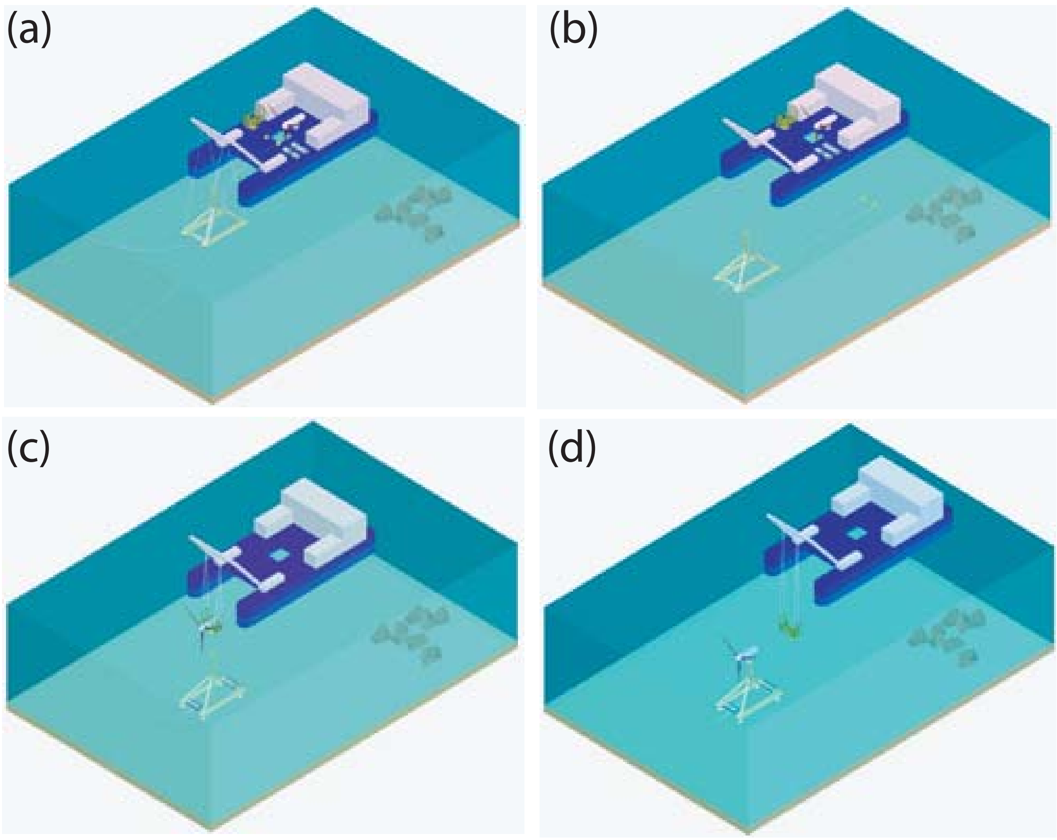

Figure 8. Installation procedure: (**a**) controlled descent of the base structure; (**b**) support structure on the seabed and deposited guide wires; (**c**) controlled descent of the nacelle; (**d**) removing the tool for nacelle installation and unstressing the guide wires.

3.4. Maintenance Procedures

For the case study developed, the following maintenance plan is considered for the tidal farm during its expected service life:

3.4.1. Blade Cleaning

The colonization of algae, microorganisms and fouling will lead to a reduction in the hydrodynamic efficiency of the rotor surfaces. Although the blades should be protected with copper paint, which acts as a biocide, one of the essential tasks is that of cleaning the blades in order to guarantee the performance of the system. The task of removing the algae, microorganisms, etc., is performed once or twice a year through the use of pressurized water in the installation vessel. It is also necessary to consider the processes of recovering and lowering the nacelle during this procedure.

3.4.2. Light Preventive Maintenance

All the components need a general maintenance and periodical inspection about every two years. We plan light preventive maintenance every two years, and this includes the following operations: changing the grease in the thrust bearing and the gearbox, filling the bottles of compressed air, inspecting all of the components, blade cleaning or checking the paint for defects.

3.4.3. High Preventive Maintenance

This procedure is more complicated than that described above, and it is necessary to perform more complex operations on the nacelle. This procedure is carried out every four years. In this case, the nacelle is moved from the tidal farm to the base port and is then completely disassembled. The following operations are carried out: bearing replacement of the thrust bearing and the gearbox, the replacement of grease in the seal ring, a detailed inspection of all the nacelle components, painting the entire nacelle, etc.

3.4.4. Corrective Maintenance

On a medium size tidal farm, it is supposed that faults may occur in a TEC that were not foreseen in the maintenance plans. The greater or lesser speed of action needed to solve the problem depends on factors such as the availability of the vessel, the particular weather window at that time, the current climate conditions and even the availability of an additional nacelle. It should be noted that, although this will probably occur, it is expected that it will be limited owing to the consideration of PTO with redundancy.

3.5. Annual Energy Produced

Bearing in mind the considerations explained in Section 2.7 as regards the estimation of the current velocity at the depth of the rotor (V_r), the performance of the power drive train (η_{PTO}), the availability factor (η_{AF}), the performance of the power export system (η_{PES}) and the tidal farm topology, the AEP obtained for the TECs in each of the four rows of which the tidal farm is composed is illustrated in Figure 9, where the following values have been taken into consideration: $Z_r = 20$ m, $Z_h = 40$ m, $C_t = 0.716$, $A_s = 452$ m^2, $A_r = 314$ m^2, $A_t = 4000$ m^2 (separation between devices of 100 m and total depth of 40 m), $D = 20$ m, $x = 30$ m, $C_P = 0.45$, $\rho = 1025$ kg/m^3, $\eta_{PTO} = 0.39$, $\eta_{AF} = 0.97$ and $\eta_{PES} = 0.946$.

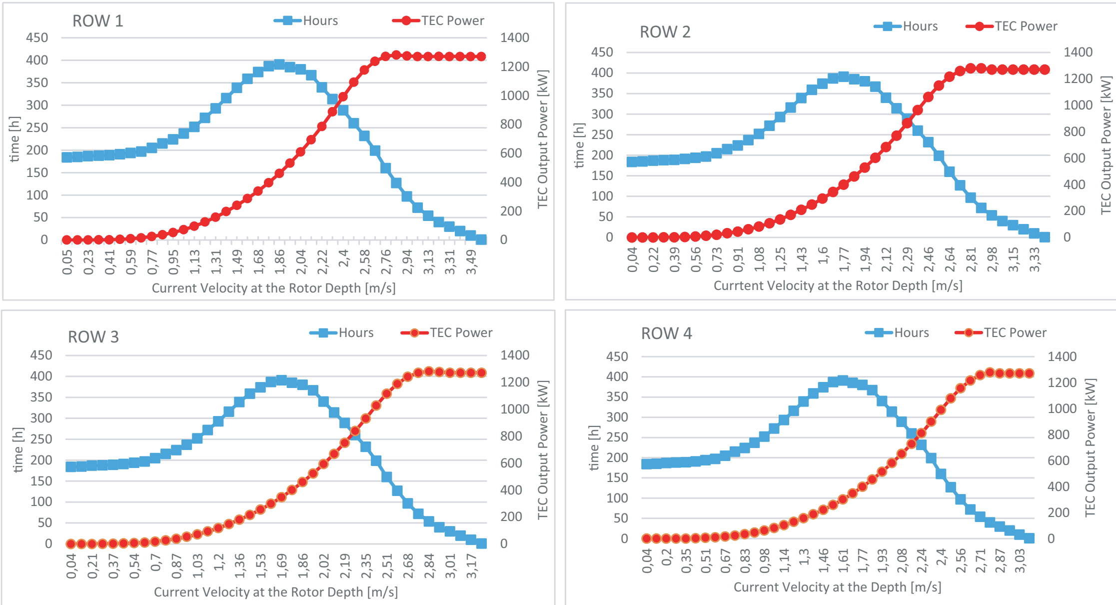

Figure 9. Energy generation of a TEC placed in the different rows of the tidal farm.

4. Numerical Results

The LCC obtained for the case study is summarized in Table 1, while all the numerical values used in the model have been included in Appendix A. Furthermore, Figure 10 depicts a percentage distribution of these costs (CAPEX and OPEX), which is highly illustrative as regards showing the offshore situation of the proposed tidal energy project. Upon analyzing the manufacturing results obtained for the tidal energy farm, which are shown in Figure 11, it will be observed that the highest costs correspond to the most important components in the energy conversion system. Furthermore, the steel used in the manufacturing process of the nacelle also makes a significant contribution to the total costs.

Table 1. Summary of the cost of the tidal farm in the Alderney Race.

Cost Category					Total Value (€)
Concept and Definition Costs (C_1)					**7,350,000**
Design and Development Costs (C_2)					**200,000**
Manufacturing Costs (C_3)					**103,613,935.88**
Nacelle					39,563,655.88
Supporting TEC Structure					21,938,280
Export Power System					42,112,000
Installation Costs (C_4)					**27,700**
Transformation Platform and Converters					3700
Submarine and Ground Exportation Cables					7200
TECs					16,800
O&M Costs (C_5)					**4,905,070.07**
	Material Costs	Transport Costs	Labor Costs	Production Losses Costs	
Blade Cleaning	0	81,120	4080	1256.40	86,456.4
Light Preventive Maintenance	142,293.45	533,512.45	53,659.63	32,394.14	761,859.67
High Preventive Maintenance	221,784.22	777,458.31	39,454.02	25,669.26	1,064,365.81
Corrective Maintenance	0	197,122.85	7068.15	10,918.47	215,109.47
Insurance Costs and Fixed Expenses					2,777,278.72
Decommissioning Costs (C_6)					**0**

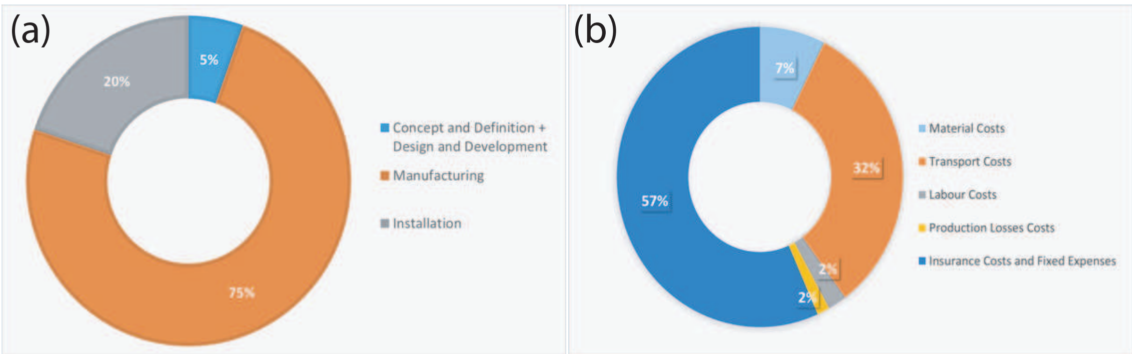

Figure 10. Cost distribution of the tidal farm: (**a**) CAPEX costs; (**b**) OPEX costs.

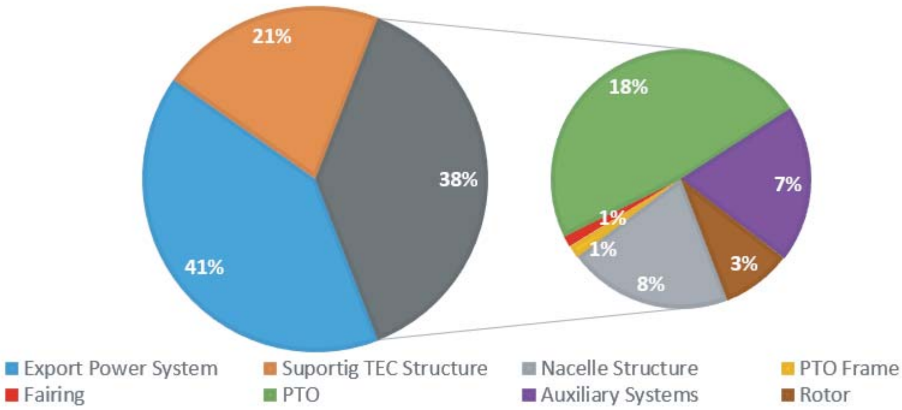

Figure 11. Manufacturing costs of the nacelle.

Furthermore, in order to study the economic indicators, the following assumptions have been considered:

- Although the current inflation values are lower than normal (typical values are between 1% and 3%), in this study, a value of 2% has been considered for the rate of inflation. This term is taken into consideration in the computation of the cash-flows through the use of the following expression [58]:

$$k = \frac{1+\hat{k}}{1+i} - 1 \tag{46}$$

  where i denotes the inflation rate and $\hat{k}$ represents the nominal annual discount rate.
- In order to attain the cash-flows, the electric tariff considered is 0.09 €/kWh, and this increases by 1.5% every year.
- All the costs are increased by 1.5% each year.
- The service life of the tidal farm considered is 20 years, although, as explained previously, if conditions for the continuation of its exploitation are favorable, it could last up to five more years.

Figure 12 illustrates different NPV curves depending on the value of the nominal interest rate k. The greater the values of the parameter k, the greater the risks and the uncertainties of the project. It will be observed that the initial investment is, in all cases recovered, between the 7.5th and 12th year. The results obtained, $NPV > 0$, $k < IRR = 0.149$ and acceptable DPBD values for all cases, indicate that the tidal energy project is economically feasible for all scenarios and that a good profitability is additionally achieved for a renewable energy project in its experimental stage.

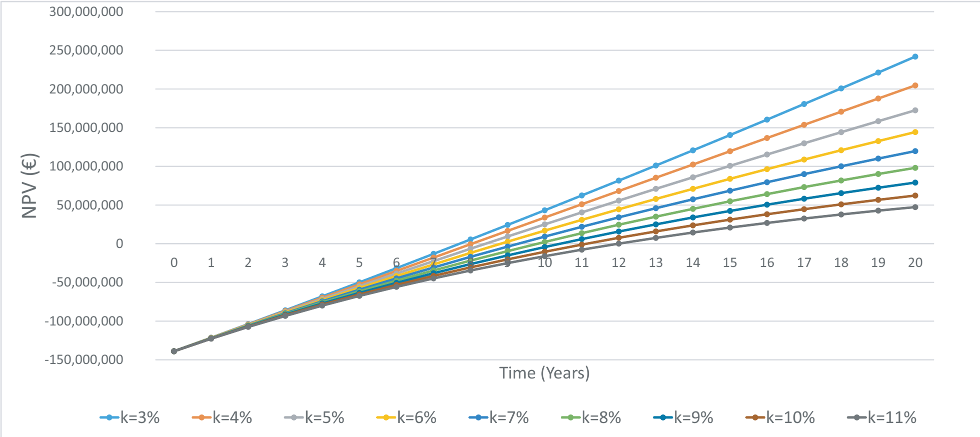

Figure 12. NPV values for different values of the rate of return in the interval between $k = 3\%$ and $k = 11\%$ and for different years of operation.

Furthermore, with regard to the technical indicators, in the case of a tidal energy project in a non-commercial stage and, therefore, with higher risks and uncertainties (high values of the k parameter), the value obtained for the LCOE indicator is close to 0.15 €/kWh (see Figure 13). This value is quite acceptable for this type of project. In fact, in the case of the current generation of devices that harness energy from the ocean currents, values of between 0.10 €/kWh and 0.20 €/kWh for the LCOE, with core values of between 0.12 €/kWh and 0.15 €/kWh are predicted [59].

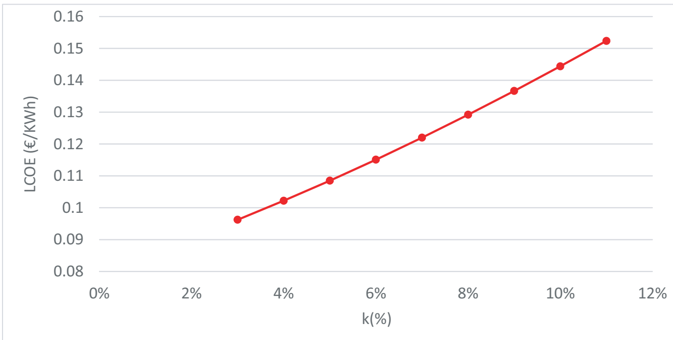

Figure 13. LCOE values for different values of the rate of return in the interval between $k = 3\%$ and $k = 11\%$.

Note that, as occurred with wind energy, there is a high margin for improvement if the installed capacity is increased and more efficient technical advances are made and exploitation procedures produced [60–63]. It is expected that when the installed capacity increases to 1 GW, the LCOE will have values of around 0.09 €/kWh (by that time, the risks and the uncertainties of the project will have been substantially reduced, moving to the smaller k values), thus making it possible to obtain cost values similar to those of the traditional renewable energy sources, whose values are between 0.05 €/kWh and 0.10 €/kWh [59].

In conclusion, after comparing all the economic and technical indicators, along with considering the commercialization of the tidal energy project, we conclude that the proposed tidal energy project is economically and technically feasible for all the case studies.

5. Conclusions

Tidal energy is a promising technological field thanks to its enormous potential for electricity production and its high predictability. Although the tidal energy industry has only just begun to demonstrate full-scale devices and device arrays, the nascent status of these technologies implies that they have not yet obtained a sufficient level of reliability, feasibility and survivability to be marketable when compared to other renewable technologies. The economic assessment of tidal energy technologies is very important as regards achieving a coherent quantification of the costs of these technologies, discovering their economic viability and simultaneously attracting investment in these technologies. It is currently complicated to find studies that focus particularly on the cost assessment and economic feasibility of tidal energy projects. In order to cover this gap, in this research, we propose a methodology for the economic assessment of tidal energy projects. This methodology is based on the LCC of these projects and proposes a cost structure that coincides with the main stages of the tidal energy project during its life-cycle. These costs are: (i) concept and definition costs; (ii) design and development costs; (iii) manufacturing costs; (iv) installation costs; (v) operation and maintenance costs; and (vi) decommissioning costs. Furthermore, these costs are subdivided into sub-cost structures, taking into consideration the main components into which the tidal farm is divided: nacelle, base support and export power system. The proposed model, meanwhile, determines the AEP (and, consequently, the incomes generated) by considering the following characteristics: (i) site current properties (speed, direction, distribution, etc.); (ii) the ability of the device to capture energy; and (iii) its ability as regards energy conversion and energy exportation. All these data are used to determine the feasibility analysis of the project with the use of different economic and technical indicators. This allows the profitability of the project to be attained along with making it possible to perform comparative studies with other renewable energy sources. The proposed methodology has been used to study the viability of a tidal farm in the Alderney Race, where the tidal resource is high. The results obtained after carrying out an analysis of the economic indicators (NPV, IRR, DPBP and LCOE) are the following: (i) the project is economically feasible for all the scenarios studied; (ii) there is good profitability for a tidal renewable energy project in an experimental phase; (iii) bearing in mind that these sorts of projects are still in their infancy, if we are able to advance in the learning curve and the installed capacity is increased (around 1 GW), a relative decrease in the installation and maintenance costs (around 30–40%) can be predicted, with an increase in the ability to capture and export tidal energy, which would lead to an increase in the profitability of the project. Finally, our future research will focus on applying this methodology to new technical solutions for tidal technologies developed by the research group in the field of the automation of emersion/immersion TEC maneuvers in order to quantify its economic viability and to attract investors.

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Appendix A. Values of the Variables Used in the Case Study

Table A1. Values of the variables in the case study.

Variable	Concept	Value	Units
C_{MR}	Market research costs	250,000	€
C_{CS}	Cost of certificates and surveys	4,000,000	€
C_{AI}	Cost per m^2 of the surfaces of the farm	2.0	€/m^2
S_{TEP}	Surface of the tidal energy farm in m^2	1,000,000 (1000 m width × 1000 m length)	m^2
C_{CDA}	Cost of conception and design analysis	600,000	€
C_{PRS}	Cost of project requirements specifications	500,000	€
C_{DD}	Cost of design and development	200,000	€
N_M	Number of TECs manufactured	43	
C_{SD}	Cost per kg of the carbon steel manufactured for the structure of the nacelle	8.0	€/kg
m_{SD}	Mass of the structure of the nacelle	23,830	kg
C_{PTOF}	Cost per kg of the manufactured carbon steel for the PTO frame	4.0	€/kg

Table A1. *Cont.*

Variable	Concept	Value	Units
m_{PTOF}	Mass of the PTO frame	3600	kg
C_F	Cost per kg of the manufactured fiberglass for the fairing	10.0	€/kg
m_F	Mass of the fairing	1240	kg
P_T	Power of each TEC	1.2	MW
C_{TB}	Cost per MW of the thrust bearing	40,000	€/MW
C_{BS}	Cost per MW of the brake system	2000	€/MW
C_{EG}	Cost per MW of the electrical generator	180,000	€/MW
C_G	Cost per MW of the gearbox	35,000	€/MW
C_{HSS}	Cost per MW of the high-speed shaft	3000	€/MW
C_{YS}	Cost per kg of the yaw system	12	€/kg
m_{YS}	Mass of the yaw system	60	kg
C_{COS}	Cost per MW of the cooling system	15,000	€/MW
C_{POS}	Cost per MW of the pressure oil system	15,000	€/MW
C_{CMS}	Cost per MW of the condition monitoring system	110,000	€/MW
C_{SWT}	Cost per kg of the protection and connection switches	12	€/kg
m_{SWT}	Mass of the protection and connection switches	124	kg
C_{CTS}	Cost per kg of the control system	12	€/kg
m_{CTS}	Mass of the control system	30	kg
C_{BIS}	Cost per kg of the bilge system	12	€/kg
m_{BIS}	Mass of the bilge system	260	kg
C_{ACS}	Cost per kg of the compressed air system	12	€/kg
m_{ACS}	Mass of the compressed air system	110	kg
C_{CB}	Cost per kg of the circuit board	12	€/kg
m_{CB}	Mass of the circuit board	90	kg
C_{AE}	Cost per kg of the added elements	3	€/kg
m_{AE}	Mass of the added elements	1000	kg
N_B	Number of blades per TEC	3	
R_R	Radius of the rotor	10	m
C_B	Cost per m of each blade	40	€/m
C_{PS}	Cost per m of the pitch system	500	€/m
C_{CR}	Cost per m of the core of the rotor	1000	€/m
C_{LSS}	Cost per m of the low-speed shaft	500	€/kg
N_I	Number of TECs installed	42	
C_{TBS}	Cost per kg of the base support of the TEC structure	3	€/kg
m_{TBS}	Mass of the base support of the TEC structure	87,200	kg
C_{TTS}	Cost per kg of the transition structure of the TEC	3	€/kg
m_{TTS}	Mass of the transition structure of the TEC	39,500	kg
C_{TVC}	Cost per kg of the vertical column of the TEC	3	€/kg
m_{TVC}	Mass of the vertical column of the TEC	29,800	kg
N_{CB}	Number of concrete ballast per TEC	2	
C_{EC}	Cost per kg of the elaborated concrete of the ballast	0.2	€/kg
m_{EC}	Mass of the concrete of the ballast	113,200	kg
N_{BG}	Number of special concrete bags per TEC	4	
C_{BG}	Cost per kg of the special concrete bags	0.3	€/kg
m_{BG}	Mass of the special concrete bags	6300	kg
C_{PSW}	Cost per MW of the protection switch	25,000	€/MW
C_{SC}	Cost per kg of the submarine connector	25	€/kg
m_{SC}	Mass of the submarine connector	300	kg
C_{BSC}	Cost per kg of the submarine connector installed in the base of the TEC	12	€/kg
m_{BSC}	Mass of the submarine connector installed in the base of the TEC	300	kg
C_{IW}	Cost per kg of the internal wiring	12	€/kg
m_{IW}	Mass of the internal wiring	150	kg
C_{CBX}	Cost per kg of the connection box	12	€/kg
m_{CBX}	Mass of the connection box	150	kg
C_{UC}	Cost per m of the umbilical cables	250	€/m
L_{UC}	Length of the umbilical cables	11,350	m
C_R	Cost per MW of the rectifiers	100,000	€/MW
C_I	Cost per MW of the inverters	100,000	€/MW
C_{EB}	Cost per MW of the electrical boxes	20,000	€/MW
N_{TF}	Number of transformers per TEC	4	
C_{TF}	Cost per MW of the transformers	40,000	€/MW
m_{TP}	Mass of the transformation platform	4,000,000	kg
C_{TP}	Cost per kg of the transformation platform	3	€/kg

Table A1. *Cont.*

Variable	Concept	Value	Units
N_{SEC}	Number of submarine exportation cables	2	
C_{SEC}	Cost per m of the submarine exportation cables	500	€/m
L_{SEC}	Length of the submarine exportation cables	11,000	m
C_{GEC}	Cost per m of the ground exportation cables	150	€/m
L_{GEC}	Length of the ground exportation cables	5000	m
$C_{V_{IPC}}$	Cost of leasing the vessels (installation of the transformation platform)	2,900,000	€
$C_{TL_{IPC}}$	Cost of technical labor (installation of the transformation platform)	300,000	€
$C_{PO_{IPC}}$	Cost of operations in the port (installation of the transformation platform)	500,000	€
$C_{V_{ISC}}$	Cost of leasing the vessels (installation of the submarine cables)	3,150,000	€
$C_{TL_{ISC}}$	Cost of technical labor (installation of the submarine cables)	150,000	€
$C_{PO_{ISC}}$	Cost of operations in the port (installation of the submarine cables)	300,000	€
$C_{V_{IGEC}}$	Cost of leasing the vessels (installation of the ground exportation cable)	3,150,000	€
$C_{TL_{IGEC}}$	Cost of technical labor (installation of the ground exportation cable)	150,000	€
$C_{PO_{IGEC}}$	Cost of operations in the port (installation of the ground exportation cable)	300,000	€
$C_{V_{ITEC}}$	Cost of leasing the vessels (installation of the TECs)	14,700,000	€
$C_{TL_{ITEC}}$	Cost of technical labor (installation of the TECs)	700,000	€
$C_{PO_{ITEC}}$	Cost of operations in the port (installation of the TECs)	1,400,000	€
C_{TBC}	Transport costs (blade cleaning)	81,120	€
C_{LBC}	Labor costs (blade cleaning)	4080	€
C_{PLBC}	Cost incurred as result of production losses (blade cleaning)	1256.4	€
C_{TLPM}	Transport costs (light preventive maintenance)	533,512.45	€
C_{LLPM}	Labor costs (light preventive maintenance)	53,659.63	€
C_{MLPM}	Material costs (light preventive maintenance)	142,293.45	€
C_{PLLPM}	Cost incurred as result of production losses (light preventive maintenance)	32,394.14	€
C_{THPM}	Transport costs (high preventive maintenance)	777,458.31	€
C_{LHPM}	Labor costs (high preventive maintenance)	39,454.02	€
C_{MHPM}	Material costs (high preventive maintenance)	22,1784.22	€
C_{PLHPM}	Cost incurred as result of production losses (high preventive maintenance)	25,669.26	€
C_{TCM}	Transport costs (corrective maintenance)	197,122.85	€
C_{LCM}	Labor costs (corrective maintenance)	7068.15	€
C_{MCM}	Material costs (corrective maintenance)	0	€
C_{PLCM}	Cost incurred as result of production losses (corrective maintenance)	10,918.47	€

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