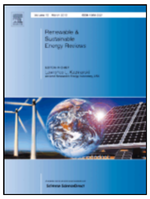
Renewable and Sustainable Energy Reviews xxx (xxxx) xxx-xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com



Study of a cost model of tidal energy farms in early design phases with parametrization and numerical values. Application to a second-generation device

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ARTICLE INFO

Keywords:
Marine renewable energy
Levelized cost of energy
Tidal energy
Ocean energy
Cost model
Cost tool

ABSTRACT

Tidal Energy Conversion farms are a promising but not yet mature technology whose costs are still highly uncertain. In order to be able to predict costs for early Technology Readiness Level (TRL) phases, this paper presents a cost model in which a detailed parametrization of all Capital Expenditures and Operation and Maintenance items has been carried out, whose results make it possible to select the best design alternative in each case. Each parameter has been updated with numerical values based on both actual and foreseen costs. A generalist tool that integrates all these parameters and that calculates, among other variables, the Levelized Cost of Energy (LCOE) has also been developed. This tool, in which the parameters have been updated, has been applied as a case study to a single-rotor GESMEY-designed generator in the case of both fixed and controllable pitch; the numerical results for the operation parameters selected are also included. The model presented in this paper is proposed in order to compare different design alternatives, under user-defined operation conditions, for tidal energy projects in early TRL phases and the effect on their LCOE.

1. Introduction

The sea has, throughout history, essentially been used for transportation and food supply. Its relevance is, nevertheless, increasing in a global world whose demand for energy grows each day. The extraction of energetic resources from the sea increased considerably in the last century, principally in the offshore oil and gas sectors. Our present concern with climate change [1] has led us to confront the great challenge of using the sea as an energy provider in a respectful manner.

Oceans are directly and indirectly the origin of many renewable energy sources; their huge surface, volume and heat capacity make them the main collector and accumulator of solar energy on our planet. The energy from the sun and the moon is accumulated in the seawater in different ways, producing various effects, some of which can be used as renewable resources [2–4].

Marine renewable energies can be classified into those that obtain the energy in the sea (marine or maritime energy), notably offshore wind energy, and those that obtain the energy produced by the sea (ocean energy). The offshore wind energy in shallow water (first-generation with devices supported on the seabed) can be considered commercially consolidated, and proven prototypes and the first commercial plants are now being built for second generation offshore wind floating devices [5].

The estimated development of ocean renewable energy in Europe for the next decade can be observed in Fig. 1, which represents the opinions of the experts surveyed (in percentages) in relation to the development of each type of energy, and can be summarized as follows [6–9]:

- Tidal dam systems are technically consolidated, although their environmental impact limits their possibilities as regards growth.
- The systems that use the thermal and saline gradient are still at a very early technological level.
- Wave energy systems have a great potential for growth, but the first offshore prototypes have had problems resisting the environment in which they are located.
- Marine current systems (inertial and tidal) will be highly developed in the forthcoming decades. The first offshore commercial tidal array, MeyGen, has been operating since 2017 [10,11].

Tidal Energy Converters (TEC) have developed considerably the technology for the first-generation systems (supported on the seabed)

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https://doi.org/10.1016/j.rser.2019.109497
Received 11 June 2018; Received in revised form 12 October 2019; Accepted 14 October 2019
Available online xxx

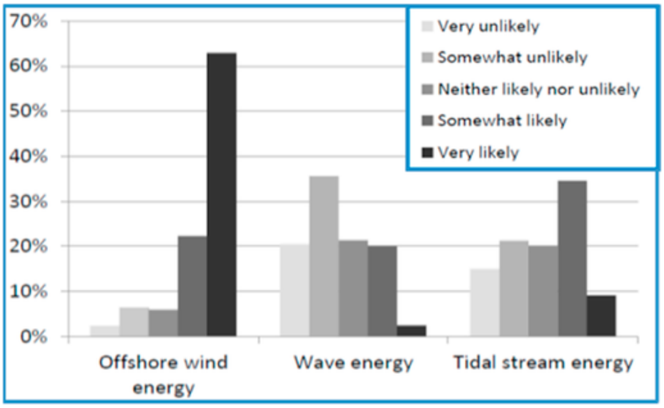


Fig. 1. Expert's predictions for the development of Marine Renewable Energies [6].

[12]. With regard to the second-generation devices (moored to the seabed), prototypes have already been tested in the sea (Fig. 2). Their development is highly relevant, since 80% of the energy from ocean currents is located in areas with depths of more than 50 m, which is a limit for the first-generation devices owing not to engineering limitations, but rather to economic viability [13].

As has occurred with wind technology, HAT-TEC devices (Horizontal Axis Turbine – Tidal Energy Converter) are being consolidated with rotors of 2 or 3 blades. In the field of HAT-TEC technology, which is applicable to first- and second-generation devices, the debate is focused on the choice of one or two high power rotors (around 1 MW) or multiple rotors (4 or more) of a lower power. It is also necessary to decide between fixed (FP) and controllable (CPR) pitch. Three parameters (TRL, TPL and LCOE) are usually employed when making decisions concerning the technical and economic viability of the different designs:

The Technology Readiness Level (TRL) was introduced by NASA [14] in order to model the technological development process of complex new systems, and is currently the standard model in research, development and innovation programmes. The NASA TRL model is one of the principal metric references involved in the development process of ocean renewable energy harnessing devices. For example, the Southampton protocol [15] is based on the TRL concept. All the TRL models require an intensive programme of simulations, model testing and prototype developments at different scales and stages.

In order to reduce the economic risks of a project, the TRL model must be completed with the Technology Performance Level (TPL) model [16,17], which measures economic and other commercial aspects of the technology being developed. Fig. 3 shows a global view of the road map estimated for some types of devices used to harness marine energy. The blue points show concrete cases, the yellow points the average trajectory, and the green points the ideal trajectory [18].

The principal objective of this paper is to propose some specific tools with which to evaluate the cost of energy at early development stages and their application to a second-generation device, which is essential in order to achieve this optimal trajectory.

In the field of renewable energy, the most important metric reference employed to measure TPL is the Levelized Cost of Energy (LCOE) [19–21], which is equal to:

$$LCOE = \frac{CP + \sum OM\cdot (1+r)^{-t}}{\sum EP\cdot (1+r)^{-t}} \tag{1}$$

where *CP* represents the CAPEX (Capital Expenditure), *OM* represents the OPEX (Operation Expenses), *EP* is the annual production of energy, *r* is the net interest rate (market minus inflation) and *t* is the time (in years) during which the TEC farm will be exploited.

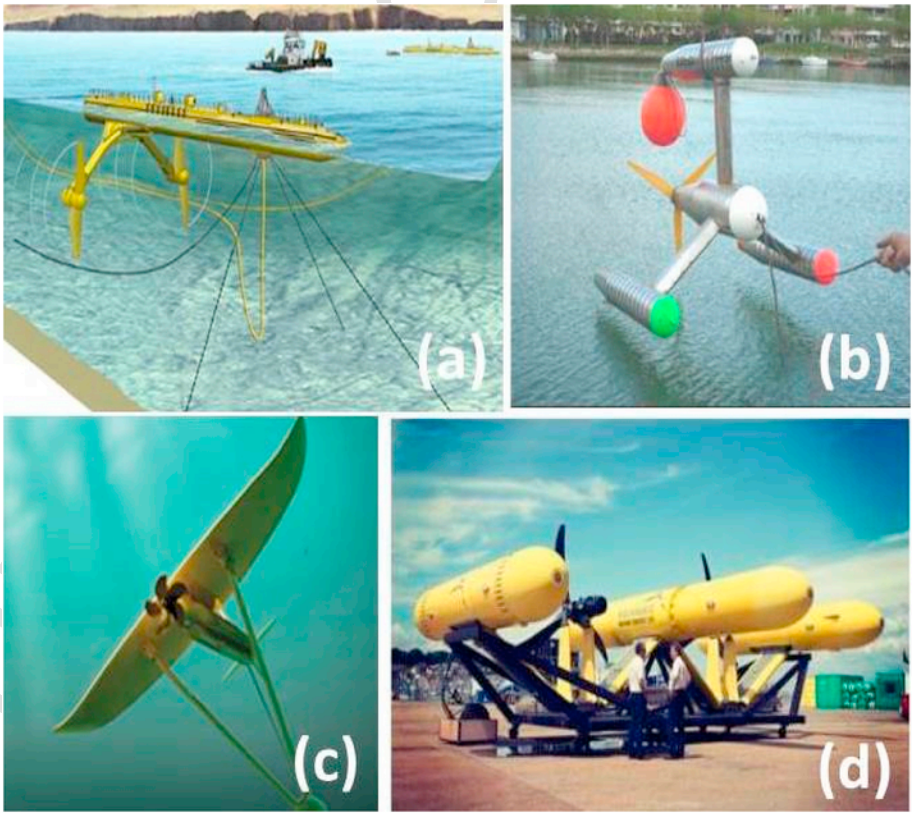


Fig. 2. Some second generation TECs: (a) Scoterenewables; (b) GESMEY; (c) Minesto and; (d) Plat-O.

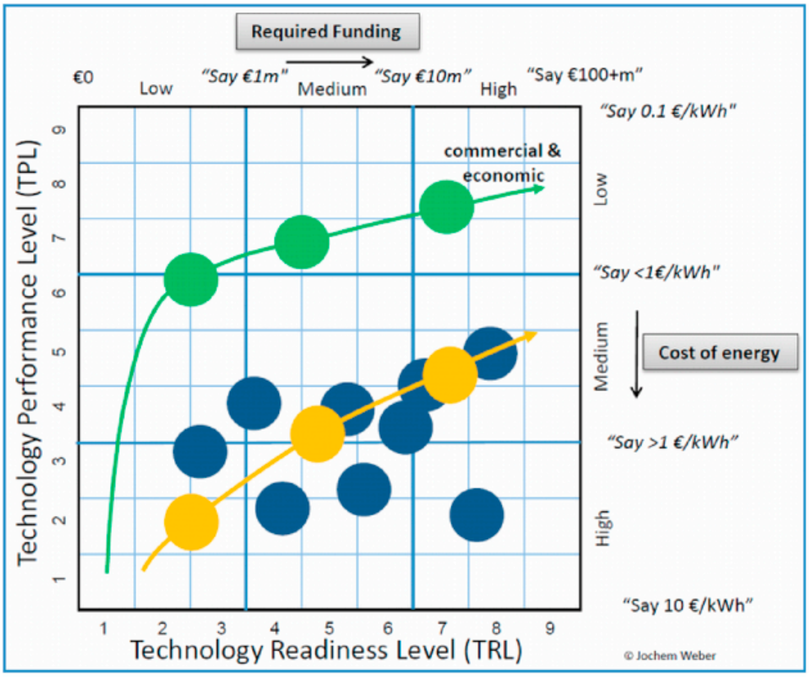


Fig. 3. Typical marine trajectories of energy device development [16].

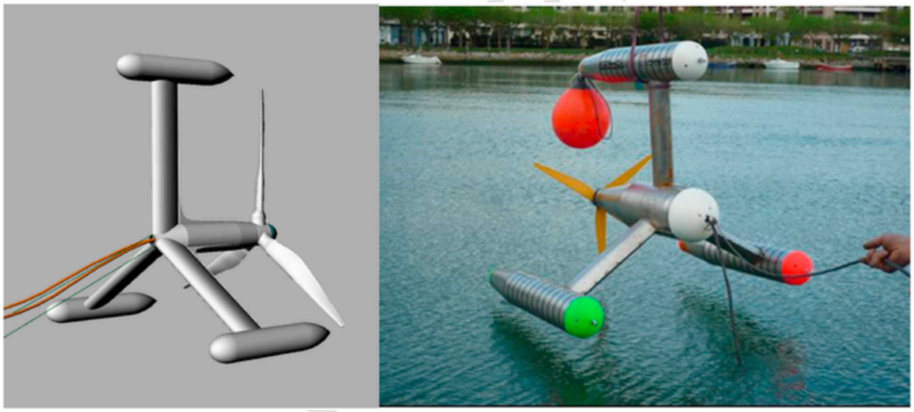


Fig. 4. (a) GESMEY 1.2 MW 3D model; (b) 1/10 scale prototype.

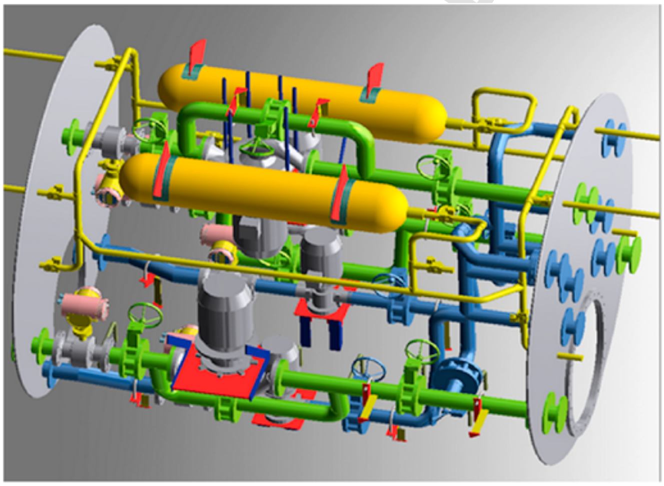


Fig. 5. Ballast Control System located in each torpedo.

The GITERM-UPM research group (Technological Innovation Group on Marine Renewable Energies from the Universidad Politécnica de Madrid) has made several contributions [22–25] to the development of second-generation devices and to the modelling of their costs in the conceptual and basic design stages. The group has, during the last few years and as part of the CODMAEH project [26,27], improved the model used to calculate the LCOE in two principal respects: a detailed modelling of the PTO costs, which allow a better comparison between the FP and CPR rotors, and the development of the operation and maintenance (O&M) costs. The following sections provide a description of this cost model, together with its application to the particular case of a single-rotor GESMEY-designed generator for both fixed and controllable pitches that is located in the English Channel, between Alderney Island and the French coast, in an area called Raz Blanchard or the Alderney Race. Please note that the TECs chosen are fully–automated floating devices, which has a great effect on the OPEX.

Section 2 presents the main characteristics of the GESMEY TEC to which the model will be applied in this work. The third section provides a detailed analysis of the parametrized costs related to the initial investment and to the operation and maintenance used in the model. In

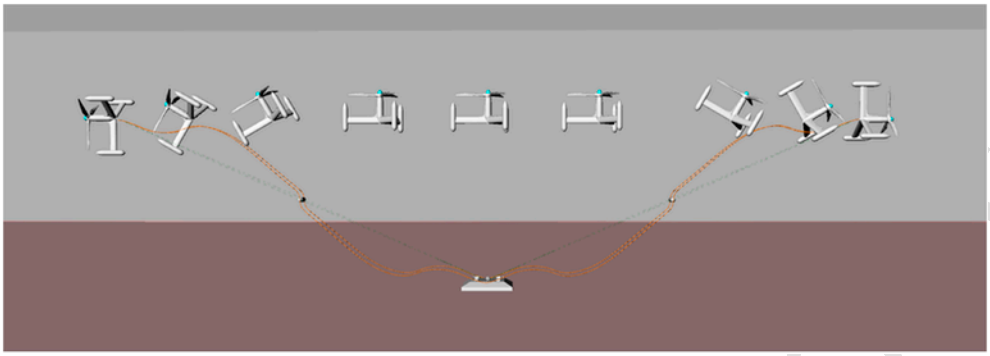


Fig. 6. GESMEY turning sequence during a change in the tidal flow. For clarity, cables are shown only in the extreme positions.

Table 1
Principal data for the Alderney Race virtual farm.

General data	
Farm nominal power (MW)	50
#TECs on the Farm	42
Farm topology	rows of 11 + 10+11 + 10 TECs
TEC dictance in row (m)	100
Row distance (m)	300
Depth to sea bottom (m)	55
Farm (Hub platform) distance to shore (km)	11
Farm distance to logistic port (nm)	18

Section 4, the model is employed to compare two different alternatives with fixed and controllable pitch, and the corresponding LCOE is obtained for each alternative, while a brief discussion of the results is shown in Section 5. The main conclusions are discussed in the sixth and final section.

2. Description of GESMEY TEC

The cost model was refined and a tool was developed for its application by selecting a TEC farm on which there are two versions of single-rotor GESMEY-designed generators, i.e. those with fixed and those with controllable pitch blades. As stated previously, this virtual farm is located on the English Channel, between Alderney Island and the French coast, in an area called Raz Blanchard or the Alderney Race. The existence of a previous study of a farm in this area [28], based on a 1.2 MW single rotor TEC with a rotating buoy mooring system [29–31], has been a source of useful data for the present study.

Fig. 8 shows the GESMEY TEC 3D model and the prototype built on a scale of 1/10. This device has been developed up to a TRL-6 level, with sea trials for a 10 kW prototype. It comprises the following elements:

- Rotor: With three blades and the hub with the pitch control actuators (this changes when fixed pitch blades are used)

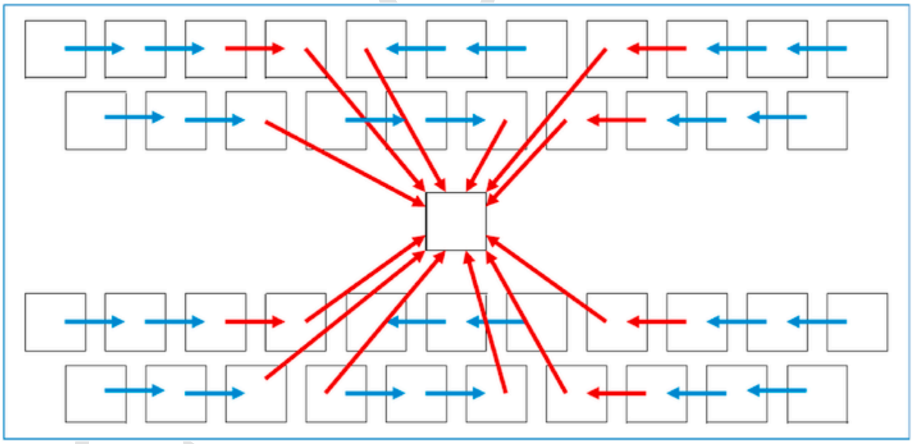
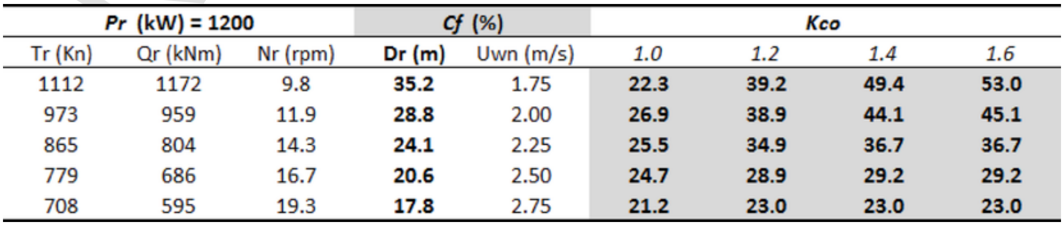


Fig. 7. Electric array layout of Alderney Race virtual farm.

Table 2
Summary of rotor diameter effect on energy production.



Pr (kW) = 1200			*Cf* (%)		*Kco*			
Tr (Kn)	Qr (kNm)	Nr (rpm)	**Dr (m)**	Uwn (m/s)	*1.0*	*1.2*	*1.4*	*1.6*
1112	1172	9.8	**35.2**	1.75	**22.3**	**39.2**	**49.4**	**53.0**
973	959	11.9	**28.8**	2.00	**26.9**	**38.9**	**44.1**	**45.1**
865	804	14.3	**24.1**	2.25	**25.5**	**34.9**	**36.7**	**36.7**
779	686	16.7	**20.6**	2.50	**24.7**	**28.9**	**29.2**	**29.2**
708	595	19.3	**17.8**	2.75	**21.2**	**23.0**	**23.0**	**23.0**

Table 3
Design data of the GESMEY TECs selected.

TEC	Tr (Kn)	Qr (kNm)	Nr (rpm)	Dr (m)	Uwn (m/s)	Cf (%)	EP (MWh)
GSY-1200-CPR	861	799	14.3	24.0	2.26	36.3	3821
GSY-1200-FP	763	666	17.2	20.0	2.55	26.6	2798

- Central nacelle: Power Take-Off (PTO) with diverse mechanical and electrical components (gearbox, electric generator, shafts, seals, bearings, and ancillary systems), based on COTS elements.
- Columns: Main structural parts and ancillary ballast tanks.
- Torpedoes (end nacelles): Three main ballast tanks with a pump room. These provide stability during operation (by means of asymmetric loading) and when afloat (like a semi-submergible platform).

An important part of the inner volume of the columns and torpedoes is used as water ballast tanks. The changes in their ballast volume make it possible to control their floatability, thus allowing the position and/or the orientation of the device to be regulated. A conceptual 3D design of the PTO is shown in Fig. 5, which depicts the constructive design of a torpedo pump room [32].

During this floatability control operation, the GESMEY TEC is maintained at the desired depth thanks to the balance of the hydrodynamic forces (rotor thrust and structure drag), the mooring cables pulling it, the weight (regulated with the ballast water) and the hydrodynamic thrust, as shown in Fig. 4. When the TEC is operating, the stability of the device is achieved thanks to the asymmetric filling of the upper torpedoes with air and the lower ones with water.

When the sea current changes its direction with the tide, the TEC turns with a quasi-inverse pendulum movement whilst maintaining its depth, as shown in Fig. 6.

For emersion (and immersion) during installation and maintenance manoeuvres, the TEC is allowed to rise from the central position of Fig. 6 to the surface by removing the ballast water. Floating maintenance can be performed in this position or, if the mooring system is disconnected, it can be transported to the shore. The inverse manoeuvres will be required for installation or re-start.

During the last few years, the GITERM-UPM group has designed and developed the details of this mooring system, improving the depth control thanks to an advanced ballast control system [33–36] that allows the TEC that is generating energy to operate at the desired depth and to automatically perform the turning, emersion and immersion manoeuvres.

Once the TEC model had been defined, a general design of the array and at least a conceptual design of the TECs took place in order to carry out a comparative cost study for a 50 MW array project in the Alderney Race. It was then necessary to complement this with a basic design of the PTO. Table 1 shows the principal data concerning the farm, while Fig. 7 shows the connection layout with a hybrid bus-star topology.

The main parameter required to size a TEC is the diameter of the rotor (D_r), as this is highly relevant as regards the energy produced (*EP*) and the cost. The different alternatives were defined by employing the yearly profile of the sea current speed in the location and the relation between power and water speed, which was composed of a parabolic curve up to the nominal power and then a horizontal line up to the cut-out speed. The result is shown in Table 2.

Here, D_r represents each diameter of the rotor, P_r represents the shaft power, T_r is the thrust, Q_r is the torque, N_r is the revolutions, C_f (grey cells) is the capacity factor, which represents the average energy production regime for a TEC located in the Alderney Race, U_{wn} is the nominal water speed and K_{co} is the relation between cut-out and nominal speed.

The table has been generated using different rotor diameters, which implies a different nominal speed to obtain the nominal power of 1.2 MW. The effect of these parameters is reflected in the "capacity factor" and in the energy generated each year. These results determine the decisions made regarding the initial design of the TEC.

These results and the GITERM-UPM group's experience with previous designs were used as a basis on which to select the following alternatives as the best options for controllable and fixed pitch:

- TEC GSY-1200-CPR (controllable pitch), with a K_{co} of 1.4, since the control system allows a wide working range from nominal to cut-out water speed.
- TEC GSY-1200-FP (fixed pitch), with a K_{co} of 1.1, taking into consideration that, when the speed is greater than the nominal one, the working depth can be increased, and a small overload can be admitted on the PTO.

The main design parameters of each TEC are shown in Table 3. The dimensions and weights of the main elements are summarized in Table 4. It must be emphasized that off the two alternatives compared, that with the fixed pitch is much simpler and has fewer maintenance costs, but it generates less energy.

3. CAPEX and OPEX model

The main variation between the different LCOE models is the internal division of the CAPEX and OPEX items that must be adapted to the device technology and the farm operation mode [37,38]. In our model, the CAPEX is divided into four main groups:

Table 4
Main data concerning the TECs analysed.

Device:		GSY-1200-CPR			GSY-1200-FP		
Item	#	Length (m)	Diameter (m)	Weight (t)	Length (m)	Diameter (m)	Weight (t)
Floating Device		15.5	28.0	101	14.2	24.0	82.7
Rotor	1		24.0	13.9		20.0	5.1
PTO Nacelle	1	12.5	2.4	32.8	11.2	2.4	29.4
Columns	3	12.0	2.5 x 1.0	24.5	10.0	2.5 x 1.0	18.4
Torpedoes	3	11.0	2.0	29.8	11.0	2.0	29.8
Mooring System							
Mooring ropes	2	75.0	0.045	2.8	75.0	0.042	2.7
Conection Buoy	1	5.0	0.8	2.0	5.0	0.8	2.0
Gravity Base	1	22.8 x 18.6 x 3.1		480	22.8 x 16.7x 3.1		430.0

Table 5
Cost of material and singular elements.

Material	Cost (k€/t)	Singular elements	Cost (k€/t)
Mild steel	3	Blades GFRP	20
Steel HT	3.5	Steel machined components	2.5
Stainless steel	7	Intermediate equipment	10
Aluminium	8	Equipments and machines	20
GFRP (Glass-Fiber Reinforced Plastic)	10	Auxiliary services	25
Reinforced concrete	0.3		
Weighted concrete	0.1		

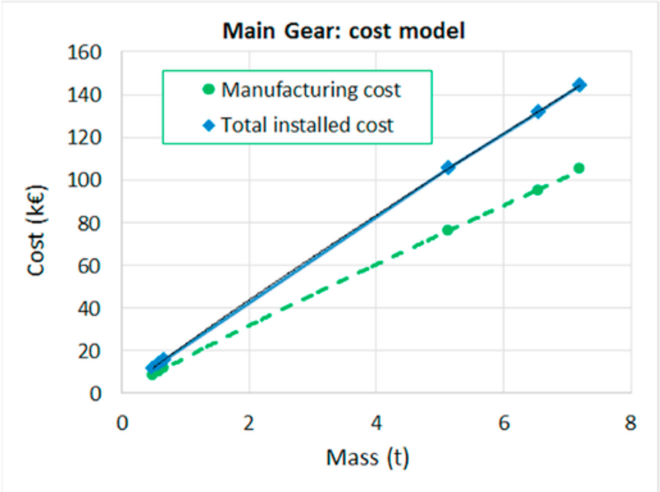


Fig. 8. Gear box cost model.

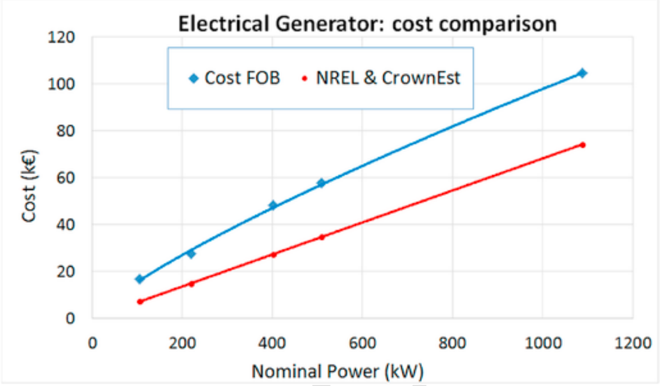


Fig. 9. Permanent magnet generator cost model.

- General costs (CP_1).
- Manufacturing and assembly (in the logistic docking bay) of the different devices, including the ancillary/mooring systems (CP_2).
- Common elements (CP_3), such as the farm hub platform and the energy transportation systems, among others.
- The on-site installation of the different devices, with the corresponding ancillary and mooring systems (CP_4).

Table 6
Summary of CP_2 parametrized costs for a GESMEY TEC.

	Base cost (k€/Parameter)	Parameter
CP_{2a} - PTO & Main Nacelle		
Blades	$0.004 \cdot Tr \cdot Dr$	$f(Tr$(kN), Dr(m))
Rotor Hub	10.0	M(t)
Pitch Control	40.0	M(t)
Seal System	25.0	M(t)
Shaft & Couplings	8.8	M(t)
Thrust bearing	25.0	M(t)
Main Gear (2–3 stages)	$23 \cdot M^{0.93}$	$f(M$(t))
Brake System	20.0	k€/t
Electric Generator	$0.39 \cdot Pn^{0.80}$	M(t)
Switchgear & Cables	8.0	$Pn(MW)$
Controlled Rectifier	25.0	Pn(MW)
Underwater Connector	20.0	M(t)
Battery Modules	8.0	M(t)
Cooling & Ancillary Equipment	25.0	M(t)
Instrument. & Control	30.0	# PLC
Structure & Nacelle Cover	3.5	M(t)
Fairing elements	10.0	M(t)
CP_{2b} - TEC Floats (& Ballast Control System)		
Pumps, valves & + +	25.0	M(t)
Electric System	*0.1*	# items
Instrument. & Control	30.0	# PLC
Nacelle & Tanks Structure	3.5	M(t)
CP_{2c} - TEC Support Structure		
Columns Structure	3.5	M(t)
CP_{2d} - Anchoring & Mooring		
Bottom platform structure	0.30	M(t)
Solid Ballast	0.15	M(t)
Underwater buoy	3.50	M(t)
Mooring System		
Galvanized Steel Ropes (45 mm diameter)	$Lr \cdot (60 + 0.25\,\mathrm{St}) \cdot 10^{-3}$	$f\,(Lr$(m), St(t))
Joints	$2 \cdot \#Ter \cdot (60 + 0.25\,\mathrm{St}) \cdot 10^{-3}$	# Terminals

Where Tr denotes the design thrust in kN, Dr the rotor diameter in m, M is the mass in metric tons, Pn is the nominal Power in MW, Lr is the rope length in m and St the nominal pulling force in metric tons.

Table 7
CP_3 parametrized costs.

	Base cost (k€/Parameter)	Parameter
$CP3_a$ - Farm Hub Platform		
Switchgear & Cables	10.0	Pn(MW)
Converter DC/AC	50.0	Pn(MW)
Offshore Substation	80.0	Pn(MW)
Ancillary Equipment	25.0	W(t)
Electric System	*0.1*	# items
Instrument. & Control	30.0	# PLC
Other Systems	8.0	Pn (MW)
Jacket Structure	$170 \cdot Pn^{0.8}$	f (Pn(kW))
Other Structural ellements	3.0	M(t)
$CP3_b$ - Energy Exportation System		
Bus array cables (DC 1 KV 1,15 KA)	$230 \cdot Lc \cdot Pn^{0,52}$	$f(Lc$(km). Pn(MW))
Hub array cables (DC 1 KV 2,3 KA)	$230 \cdot Lc \cdot Pn^{0,52}$	$f(L$(km). Pn(MW))
Export cables (AC 300 KV 25 MW x2)	$50 \cdot Lc \cdot Pn^{0,5}$	$f(L$(km). Pn(MW))
Land Substation (no voltage change)	20.0	Pn(MW)
Land cables (including lay out)	$30 \cdot Lc \cdot Pn^{0,5}$	$f(L$(km). Pn(MW))

Where Lc denotes the cable length in km and Pn the cable's nominal power in MW.

The four main cost groups will be analysed in this section, providing scalable formulas for each of the components of the TECs mentioned above, with the aim of improving and updating the previous cost analysis of all the elements involved in the energy production system.

Table 8
Oceanic operations costs.

Oceanic operations cots	k€/day
Light size maintenance vessel	2
Mid size maintenance vessel	4
Harbour tug	4
Oceanic tug	4
Anchor laying vessel	60
Submarine works vessel	60
Jack-up high loads installation	150
Jacket structure installation	180
High load installation DP floating	320
Array cable-laying vessel	95
Cable laying vessel	120
Own technicians	0.6
External technician specialists	1

Table 9
CP_{4a} vessels and operation times.

Operation		Maintenance vessel	Tug-1	Tug-2	Tug-3	Hopper dredger
	Trip to location from harbour	1.5	4.0	4.0	1.5	1.5
Platform 1	Platform descent	2.0	2.0		2.0	
	Vessel change	0.5				0.5
	Base filled with concrete	2.0				2.0
	Cable recovery					1.0
Platform 2	Platform descent	2.0		2.0	2.0	
	Vessel change	0.5				0.5
	Base filled with concrete	2.0				2.0
	Cable recovery					1.0
	Return to harbour	1.5	1.5	1.5	1.5	1.5
Total		12.0	7.5	7.5	7.0	10.0

Table 10
CP_{4b} Vessels and operation times.

Operation	Maintenance vessel	Harbour tug
Trip to location from harbour	1.5	4.0
Connecting mooring cables	2.0	2.0
Connecting umbilical cables	2.0	
Start-up operations	1.0	
Return to harbour	1.5	1.5
Total	8.0	7.5

3.1. General costs (CP_1)

The following items are normally considered to be general costs:

- Techno-economic feasibility analysis.
- Attainment of all necessary permits and concessions needed to install and operate the farm.
- Financing process of the project, which can be ensured via different types of investors.
- All initial studies, such as environmental surveys, coastal process surveys, station surveys, seabed surveys, human impact studies, logistic studies, etc. [39].
- Global design engineering and contracting of equipment and service suppliers.
- Cost of bank bonds to cover the decommissioning of the plant at the end of its life. It is highly probable that the devices will not be reused, but rather recycled and sold as scrap. The price of scrap steel allows us to assume that the actual dismantling cost will be compensated by the value of the material [40].

It is usually very difficult to establish a generic value of the CP_1, since it depends on the characteristics of the project to be developed, the type of installation and the location [41]. The General Costs are often considered to be a percentage of the CAPEX, and are eventually an average value of 5% for the TECs [42]. Based on this, the CP_1 could be calculated with the following formula:

$$CP_1 = 0.05 \cdot CAPEX \tag{2}$$

3.2. Cost of devices and singular elements (CP_2)

In order to facilitate their installation and maintenance, most TECs are divided in two main sets: the extractable or moored device that generates the energy (with the rotor and main nacelle) and the system that connects this device to the seabed. In the case of GESMEY TEC, the two sets are the floating unit that holds the Power Take Off (PTO) and the mooring system (ropes, umbilical and gravity anchor).

The cost of the different items has been calculated by employing the data provided by the Crown Estate [39] and NREL [43] studies. As the costs in the Crown Estate study were in 2010 pounds sterling and those in the NREL study were in 2006 dollars, it has been necessary to update the given costs to December 2017 euros. A more in-depth analysis has been carried out for the main equipment, such as the gear box and the generator, by comparing the cost curves from the references with the cost curve obtained from offers provided by manufacturers.

Since it is not always easy to obtain direct data it has, on some occasions, been necessary to estimate the cost of the singular element with reference to its weight, using the values shown in Table 5.

As stated previously, the gear box is one of the most critical elements in the PTO and the cost curve has, therefore, been calculated using the actual cost of six Flender Planurex's planetary gear boxes, obtaining a good regression among them. A scale factor of 1.38 has been used to include the integration cost, and the result has been checked with a gear box on a 5 MW wind farm from the Crown Estate study and with one of 1.2 MW from the NREL study, obtaining similar results. The regression obtained is shown in Fig. 4, obtaining a cost in k€ of:

$$CP_{2a-gear\ box} = 23 \cdot M^{0.93} \tag{3}$$

where M represents the mass of the gear box in metric tons.

The curve cost of the electric generator has been attained using data regarding five real permanent magnet generators obtained from the manufacturers Siemens and Leroy Somers, which have different types of refrigeration and speed. The values obtained are slightly higher than those in the references and the decision was consequently made to use the regression with the actual values, as shown in Fig. 9, resulting in a cost in k€ of:

$$CP_{2a-generator} = 0.39 \cdot Pn^{0.80} \tag{4}$$

where Pn stands for the power of the PTO in kW.

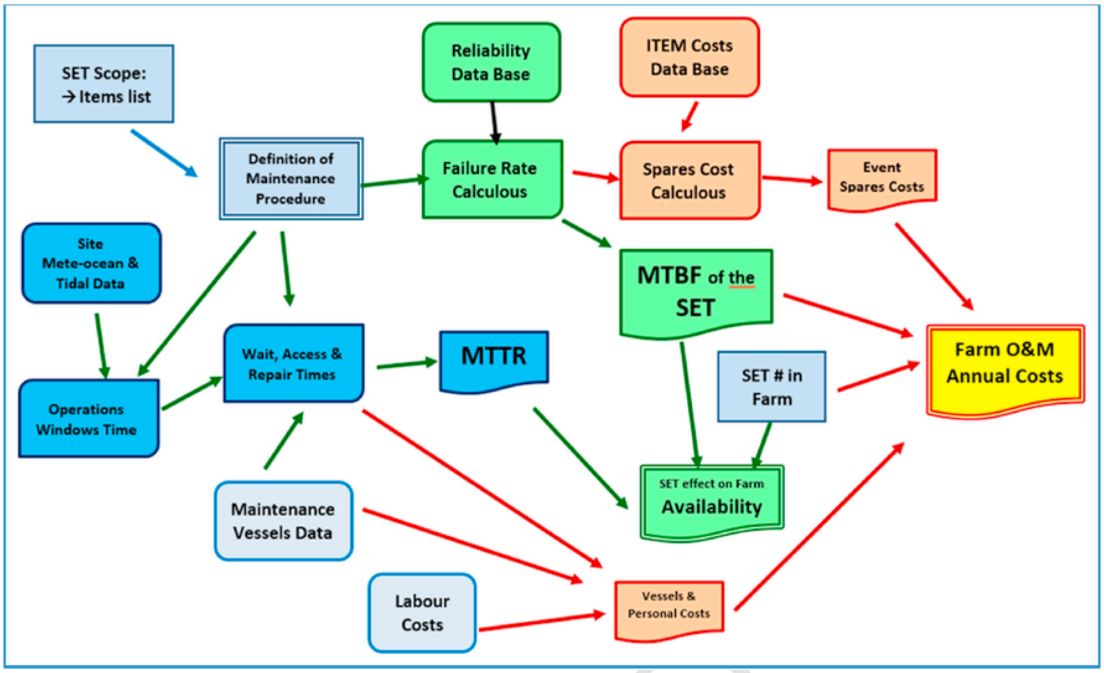


Fig. 10. OA&MC (Operation Availability & Maintenance Costs) model.

Table 11
GSY-1200-CPR rotor and main nacelle failure rates.

	$\lambda_{equipment}$	*Nº*	*Redundancy*	$K_{operation}$	$\lambda_{operation}$
GSY-1200-CPR rotor and main nacelle failure rates					
Blades	0.130	3	1	0.90	0.351
Rotor Hub	0.150	1	1	0.90	0.135
Pitch Control	0.350	1	1	0.90	0.315
Seal System	0.060	1	1	0.90	0.054
Shaft & Couplings	0.055	1	1	0.90	0.050
Thrust bearing	0.100	1	1	0.90	0.090
Main Gear (2–3 stages)	0.240	1	1	0.95	0.228
Brake System	0.100	1	1	0.10	0.010
Electric Generator	0.450	1	1	0.90	0.405
Switchgear & Cables	0.191	1	1	0.90	0.172
Controlled Rectifier	0.200	1	1	0.90	0.180
Underwater Connector	0.090	2	1	1.00	0.180
Battery Modules	0.250	1	2	0.20	0.025
Ancillary Equipment	0.230	1	2	1.00	0.115
Instrument. & Control	0.700	1	3	1.00	0.233
Structure & Nacelle Cover	0.001	1	1	1.00	0.001
Fairing elements	0.001	1	1	1.00	0.001
$\lambda_{operation}$ **(failure/year)**					**2.545**

Table 12
GSY-1200-CPR Offshore maintenance phases.

	time (h)
GSY-1200-CPR Offshore maintenance phases	
Failure detection, technicians and spares transport	1.0
Sailing from harbour to the farm	1.5
Offshore repairs	4.0
Sailing back to harbour	1.5
$MTTR_{minimum}$	6.5

The parametrized cost of the remaining elements has been estimated using either a direct calculation taken from the material and the type of singular element, or the updated information from the Crown Estate model and other sources, or by employing a combination of both.

Table 13
GSY-1200 TEC In-dock maintenance phases.

	time (h)
GSY-1200-CPR In-dock maintenance phases	
Sailing from harbour to farm	1.5
Floating works	5.0
Sailing to harbour	1.5
Works on dock	32.0

As an example, the parametrized cost of the devices and singular elements for a GESMEY TEC is summarized in Table 6.

3.3. Cost of the hub platform and the energy transportation systems (CP_3)

This group includes the elements that allow the transportation of the energy generated by the PTO to the grid onshore. The submarine cabling of the farm array can have many connection typologies between the different devices and the hub platform. Dynamic type three-phase cables are normally used, with voltages between 1 kV and 50 kV. The export submarine cables are usually of the static and high–voltage type (normally above 100 kV). The parametrized cost of the Farm Hub Platform elements and the Energy Exportation cables and substations is summarized in Table 7.

3.4. Cost of installation on-site (CP_4)

It is difficult to estimate the installation costs for tidal farms owing to the special characteristics and uncertainties of offshore operations; these are subject to the weather conditions and to the fluctuating costs of the vessels used, which are in turn subject to changes in the shipping market. The installation cost also greatly depends on the mooring system and on the oceanic operations strategy.

In order to define the installation strategy, it is necessary to predefine the base port. This will, in our case, be Cherbourg harbour in the English Channel in north-western France, which is located only at 18 miles from the Alderney Race, the farm location chosen.

Table 14
CAPEX costs for the GSY-1200-CPR central nacelle.

CP_{2a} PTO & Main Nacelle	Base cost *(k€/Parameter)*	Parameter	Value	Cost (k€)	Comments
Blades	*0.004·Tr·Dr*	*Tr* (kN)	861	82.7	3 with composite structure
Rotor Hub	10	*M* (t)	9.30	93.0	
Pitch Control	40	*M* (t)	0.50	20.0	
Seal System	25	*M* (t)	0.24	6.0	
Shaft & Couplings	8.8	*M* (t)	3.90	34.3	
Thrust bearing	25	*M* (t)	0.25	6.3	
Main Gear	$23\,M^{0.93}$	*M* (t)	6.55	132.1	
Brake System	20	*M* (t)	0.77	15.4	Electrical in generator shaft
Electric Generator	$0.39 \bullet Pn^{0.80}$	*Pn* (kW)	1088	104.8	Permanent Magnet Synchronous Generator
Switchgears & Cables	8.0	*Pn* (MW)	1.10	8.8	Main brk (5) Disconect. (2) Cabl. (1)
Controlled Rectifier	25	*Pn* (MW)	1.10	27.5	
Underwater Connector	20	*M* (t)	0.20	4.0	
Battery Modules	8.0	*M* (t)	0.10	0.8	for Brake system
Ancillary Equipment	25	*M* (t)	0.60	15.0	gear & PMG refrigeration & other
Instrument. & Control	30	# PLC	3	90.0	
Structure & Nacelle Cover	3.5	*M* (t)	15.30	53.6	
Fairing elements	10	*M* (t)	0.40	4.0	2x200kg
	Items/TEC	1		698	CP_{2a} Cost (k€/TEC)

Table 15
CAPEX costs for the farm transformer platform.

CP_{2b} TEC Floats (& Ballast Control System)	Base cost *(k€/Parameter)*	Parameter	Value	Cost (k€)	Comments
Pumps, valves & + +	25	M (t)	1.20	**30.0**	*Located in pump room*
Electric System	*0.1*	# items	30	3.0	
Instrument. & Control	30	# PLC	3	90.0	
Nacelle & Tanks Structure	3.5	M (t)	8.50	29.8	*HT steel*
	Items/TEC	**3**		**458**	**CP_{2b} Cost (k€/TEC)**

Table 16
Installation and commissioning costs for a GESMEY TEC.

CP_{4b}: TEC Installation & Commissioning	k€/day	Units	Days	Cost (k€)
Light size maintenance vessel	2			0.0
Mid size maintenance vessel	4	1	1.0	4.0
Harbour tug	4	1	1.0	4.0
Oceanic tug	15			0.0
Anchor laying Ship	60			0.0
Submarine works Ship	60			0.0
Jack-up High loads installation	150			0.0
Jacket struct. Installation	180			0.0
High load installation DP floating	320			0.0
Array Cable-Laying Vessel	95			0.0
Cable-Laying Ship	120			0.0
Special ships 1	0			0.0
Special ships 2	0			0.0
Own Technicians	0.6	4	1.0	2.4
External Technician Specialists	1.0			0.0
Weather & Logistics Delays Coefficient (40% weather + 20% logistics delays + 10% margin)				1.7
CP_{4b} Cost (k€/TEC)				17.7

Table 17
Summary of GSY-1200-CPR OPEX costs.

TEC type - model:GSY-1200-CPR
Farm location:Alderney Race

Summary OPEX costs by year		#	k€/unit	Farm
Fixed Farm Costs	OM_{1a}	*1,5% CAPEX*		M€/year
Land Workshop	OM_{1b}			0.50
Floating Dock	OM_{1c}			0.61
PTO Nacelle offhore repairs	OM_{2a}	42	23.35	0.98
Ballast CS offshore repairs	OM_{2b}	126	10.27	1.29
TEC repairs on floating dock	OM_{2c}	42	66.00	2.77
Mooring system repairs	OM_{2d}	42	11.24	0.47
P-Hub systems repairs	OM_{3a}	1	520.84	0.52
Submarine cables reparation	OM_{3b}	1	1204.09	1.20

The proposed method can obviously be used in other locations by changing only the appropriate parameters.

As has been shown in previous works [28,42], in order to calculate the installation costs it is necessary to define the installation processes with their main phases, estimating the required times, vessels and technicians needed for each one.

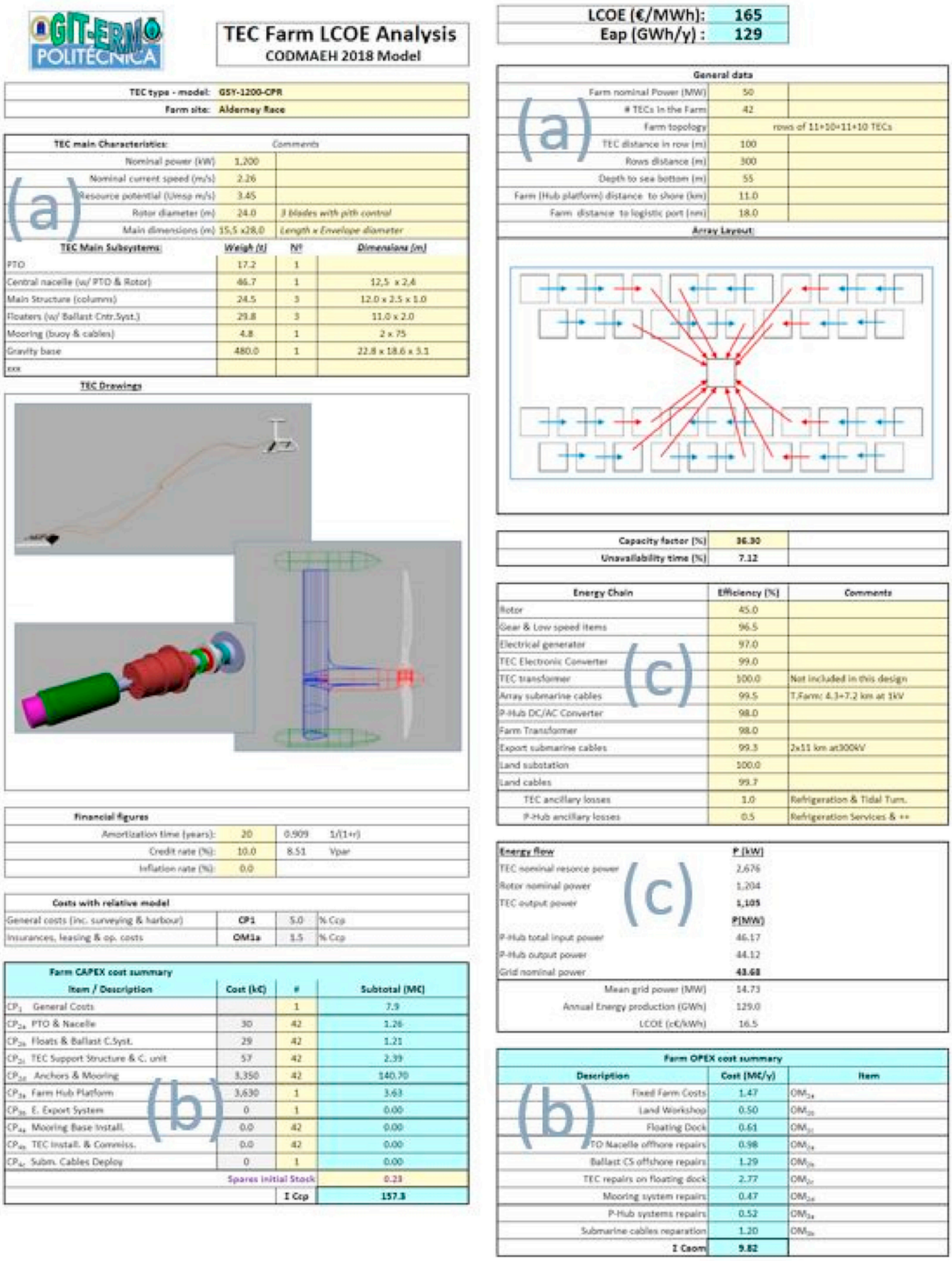
Once the operation times and resources (vessels and technicians) have been defined, the cost can be calculated using the values shown in Table 8. It is again important to stress that the cost of leasing the vessels is highly variable and can change even during the execution of the project.

In the present study, the installation cost has three main concepts: the installation of the submarine base and the anchoring and mooring (CP_{4a}), the installation and commissioning cost of the TECs (CP_{4b}) and the deployment of the umbilical cables (CP_{4c}), all of which are detailed in the following sections.

3.4.1. Installation of the submarine base and the anchoring and mooring (CP_{4a})

The installation procedure of a mooring system for a second-generation device entails a first stage in which the mooring, guide and towing cables are connected to the submarine base in the base port before it is towed to the site with the help of a harbour tug. Once on the chosen site, two tugs provided with dynamic position systems are needed to smoothly sink the base onto the seabed. The submarine operation can be monitored with remotely operated devices (ROVs). The operation concludes with a hopper dredger, which fills the base with concrete, sand and gravel with the help of a maintenance vessel and the concreting guide cable.

This operation strategy can be optimized if three tugs are used rather than two (two to transport the platforms and one to support their placement on the seabed). With this strategy, rather than leasing two tugs during two days to install two platforms, the operation can be carried out in one day with three tugs. The vessels employed and the operation hours are shown in Table 9.



TEC Farm LCOE Analysis
CODMAEH 2018 Model

TEC type - model:	GSY-1200-CPR
Farm site:	Alderney Race

TEC main Characteristics:		Comments
Nominal power (kW)	1,200	
Nominal current speed (m/s)	2.26	
Resource potential (Umsp m/s)	3.45	
Rotor diameter (m)	24.0	3 blades with pith control
Main dimensions (m)	15,5 x28,0	Length x Envelope diameter

TEC Main Subsystems:	Weigh (t)	Nº	Dimensions (m)
PTO	17.2	1	
Central nacelle (w/ PTO & Rotor)	46.7	1	12,5 x 2,4
Main Structure (columns)	24.5	3	12.0 x 2.5 x 1.0
Floaters (w/ Ballast Cntr.Syst.)	29.8	3	11.0 x 2.0
Mooring (buoy & cables)	4.8	1	2 x 75
Gravity base	480.0	1	22.8 x 18.6 x 3.1
xxx			

TEC Drawings

Financial figures			
Amortization time (years):	20	0.909	1/(1+r)
Credit rate (%):	10.0	8.51	Vpar
Inflation rate (%):	0.0		

Costs with relative model			
General costs (inc. surveying & harbour)	CP1	5.0	% Ccp
Insurances, leasing & op. costs	OM1a	1.5	% Ccp

Farm CAPEX cost summary			
Item / Description	Cost (k€)	#	Subtotal (M€)
CP_1 General Costs		1	7.9
CP_{2a} PTO & Nacelle	30	42	1.26
CP_{2b} Floats & Ballast C.Syst.	29	42	1.21
CP_{2c} TEC Support Structure & C. unit	57	42	2.39
CP_{2d} Anchors & Mooring	3,350	42	140.70
CP_{3a} Farm Hub Platform	3,630	1	3.63
CP_{3b} E. Export System	0	1	0.00
CP_{4a} Mooring Base Install.	0.0	42	0.00
CP_{4b} TEC Install. & Commiss.	0.0	42	0.00
CP_{4c} Subm. Cables Deploy	0	1	0.00
		Spares Initial Stock	0.23
		Σ Ccp	157.3

LCOE (€/MWh):	165
Eap (GWh/y) :	129

General data		
Farm nominal Power (MW)	50	
# TECs in the Farm	42	
Farm topology		rows of 11+10+11+10 TECs
TEC distance in row (m)	100	
Rows distance (m)	300	
Depth to sea bottom (m)	55	
Farm (Hub platform) distance to shore (km)	11.0	
Farm distance to logistic port (nm)	18.0	

Array Layout:

Capacity factor (%)	36.30	
Unavailability time (%)	7.12	

Energy Chain	Efficiency (%)	Comments
Rotor	45.0	
Gear & Low speed items	96.5	
Electrical generator	97.0	
TEC Electronic Converter	99.0	
TEC transformer	100.0	Not included in this design
Array submarine cables	99.5	T.Farm: 4.3+7.2 km at 1kV
P-Hub DC/AC Converter	98.0	
Farm Transformer	98.0	
Export submarine cables	99.3	2x11 km at300kV
Land substation	100.0	
Land cables	99.7	
TEC ancillary losses	1.0	Refrigeration & Tidal Turn.
P-Hub ancillary losses	0.5	Refrigeration Services & ++

Energy flow	P (kW)
TEC nominal resorce power	2,676
Rotor nominal power	1,204
TEC output power	1,105
	P(MW)
P-Hub total input power	46.17
P-Hub output power	44.12
Grid nominal power	43.68
Mean grid power (MW)	14.73
Annual Energy production (GWh)	129.0
LCOE (c€/kWh)	16.5

Farm OPEX cost summary		
Description	Cost (M€/y)	Item
Fixed Farm Costs	1.47	OM_{2a}
Land Workshop	0.50	OM_{2b}
Floating Dock	0.61	OM_{2c}
PTO Nacelle offhore repairs	0.98	OM_{3a}
Ballast CS offshore repairs	1.29	OM_{3b}
TEC repairs on floating dock	2.77	OM_{3c}
Mooring system repairs	0.47	OM_{3d}
P-Hub systems repairs	0.52	OM_{4a}
Submarine cables reparation	1.20	OM_{4b}
Σ Csom	9.82	

Fig. 11. Spreadsheet output summary.

Real data regarding inoperability as the result of weather conditions in the North Sea that would affected vessels of similar size to those used in this operation were analysed. The results were adapted to real statistical data in the Alderney Race area. Employing this as a basis, and in order to calculate the margins, it can be assumed that 40% of the days/year are not suitable for operation in the Alderney Race area owing to adverse weather conditions; if the installation takes place during the summer, only 20% of the time will not be suitable for work. A 10% time increase can be added to cover logistic delays and another 10% to cover the cost of the trip made by the lease vessels to the area and other unforeseen costs.

3.4.2. Installation and commissioning cost of the TECs (CP_{4b})

In order to perform the process of installing and commissioning the TECs, a favourable climatic window and sea currents with speeds below 1 m/s are necessary. A team of workers can connect only one device per day. The vessels employed and the operation hours are shown in Table 10.

Table 18
(a) Spreadsheet output. TEC main data.

TEC type - model:	GSY-1200-CPR		
Farm site:	Alderney Race		
TEC main Characteristics:	*Comments*		
Nominal power (kW)	1200		
Nominal current speed (m/s)	2.26		
Resource potential (Umsp m/s)	3.45		
Rotor diameter (m)	24.0	*3 blades with pith control*	
Main dimensions (m)	15.5 x28.0	*Length x Envelope diameter*	
TEC Main Subsystems:	*Weigh (t)*	*Nº*	*Dimensions (m)*
PTO	17.2	1	
Central nacelle (w/PTO & Rotor)	46.7	1	12.5 x 2.4
Main Structure (columns)	24.5	3	12.0 x 2.5 x 1.0
Floaters (w/Ballast Cntr.Syst.)	29.8	3	11.0 x 2.0
Mooring (buoy & cables)	4.8	1	2 x 75
Gravity base	480.0	1	22.8 x 18.6 x 3.1
General data			
Farm nominal Power (MW)	50		
# TECs on Farm	42		
Farm topology	rows of 11 + 10+11 + 10 TECs		
TEC distance in row (m)	100		
Rows distance (m)	300		
Depth to sea bottom (m)	55		
Farm (Hub platform) distance to shore (km)	11.0		
Farm distance to logistic port (nm)	18.0		

Table 19
(b) Spreadsheet output. CAPEX and OPEX.

Costs with relative model			
General costs (inc. surveying & harbour)	**CP1**	5.0	% Ccp
Insurances, leasing & op. costs	**OM_{1a}**	1.5	% Ccp
Farm CAPEX cost summary			
Item /Description	**Cost (k€)**	#	**Subtotal (M€)**
CP_1 General Costs		1	4.7
CP_{2a} PTO & Nacelle	698	42	29.32
CP_{2b} Floats & Ballast C.Syst.	458	42	19.25
CP_{2c} TEC Support Structure & C. unit	86	42	3.62
CP_{2d} Anchors & Mooring	111	42	4.66
CP_{3a} Farm Hub Platform	12,552	1	12.55
CP_{3b} E. Export System	11,688	1	11.69
CP_{4a} Mooring Base Install.	30.4	42	1.28
CP_{4b} TEC Install. & Commiss.	17.7	42	0.74
CP_{4c} Subm. Cables Deploy	6810	1	6.81
		Spares initial Stock	**3.32**
		Σ Ccp	**98.0**

Farm OPEX cost summary		
Description	Cost (M€/y)	Item
Fixed Farm Costs	1.47	OM_{1a}
Land Workshop	0.50	OM_{1b}
Floating Dock	0.61	OM_{1c}
PTO Nacelle offhore repairs	0.98	OM_{2a}
Ballast CS offshore repairs	1.29	OM_{2b}
TEC repairs on floating dock	2.77	OM_{2c}
Mooring system repairs	0.47	OM_{2d}
P-Hub systems repairs	0.52	OM_{3a}
Submarine cables reparation	1.20	OM_{3b}
Σ Caom	**9.82**	

Table 20
(c) Spreadsheet output. Efficiency and energy.

Capacity factor (%)	36.30	
Unavailability time (%)	7.12	
Energy Chain	Efficiency (%)	*Comments*
Rotor	45.0	
Gear & Low speed items	96.5	
Electrical generator	97.0	
TEC Electronic Converter	99.0	
TEC transformer	100.0	Not included in this design
Array submarine cables	99.5	T.Farm: 4.3 + 7.2 km at 1 kV
P-Hub DC/AC Converter	98.0	
Farm Transformer	98.0	
Export submarine cables	99.3	2x11 km at300kV
Land substation	100.0	
Land cables	99.7	
TEC ancillary losses	1.0	Refrigeration & Tidal Turn.
P-Hub ancillary losses	0.5	Refrigeration Services & + +
Energy flow	P (kW)	
TEC nominal resorce power	2676	
Rotor nominal power	1204	
TEC output power	1105	
	P (MW)	
P-Hub total input power	46.17	
P-Hub output power	44.12	
Grid nominal power	43.68	
Mean grid power (MW)	14.73	
Annual Energy production (GWh)	129.0	
LCOE (c€/kWh)	16.5	

Table 21
Comparative summary of the GSY-1200-CPR and GSY-1200-FP.

Comparison for farms based on TECs: GSY-1200				
		CPR	FP	% Delta
CAPEX	(M€)	98	89	−9.2%
OPEX	(M€/y)	9.82	8.46	−13.8%
Capacity factor	(%)	36.3	26.6	−26.7%
Unavailability time	(%)	7.12	6.57	−7.7%
Eap	(GWh/y)	129	93	−27.9%
LCOE	(€/MWh)	165	204	23.6%

Upon considering the aforementioned strict climatic and current restrictions for this operation, the cost should be increased by 40% owing to adverse weather conditions and by another 20% in order to take into account logistic delays resulting from the complexity of the devices.

3.4.3. *Energy exportation system - deployment of the umbilical cables (CP_{4c})*

A medium-size laying vessel is required to install the umbilical array cables among the devices and between the devices and the platform hub. According to the knowledge acquired from offshore wind farms [44], the average cost of laying a cable is currently around 0.4 M€/km, and around 15 h are required to install one inter-array cable [45]. This cost must be increased for the whole farm with the cable loading time of around six periods of two days, and the three days needed to travel from the base harbour to Cherbourg harbour.

Assuming an operation speed of 2 knots, the installation of each exportation cable between the platform hub and the shore will require around three days. An extra five days are also needed to load the cable vessel and travel to the Alderney Race.

The larger size of the ships used in this operation signifies that it is possible to assume a lower cost increase of only 20% for adverse weather conditions, and another 10% for logistic delays, as only one cable supplier is involved in this operation.

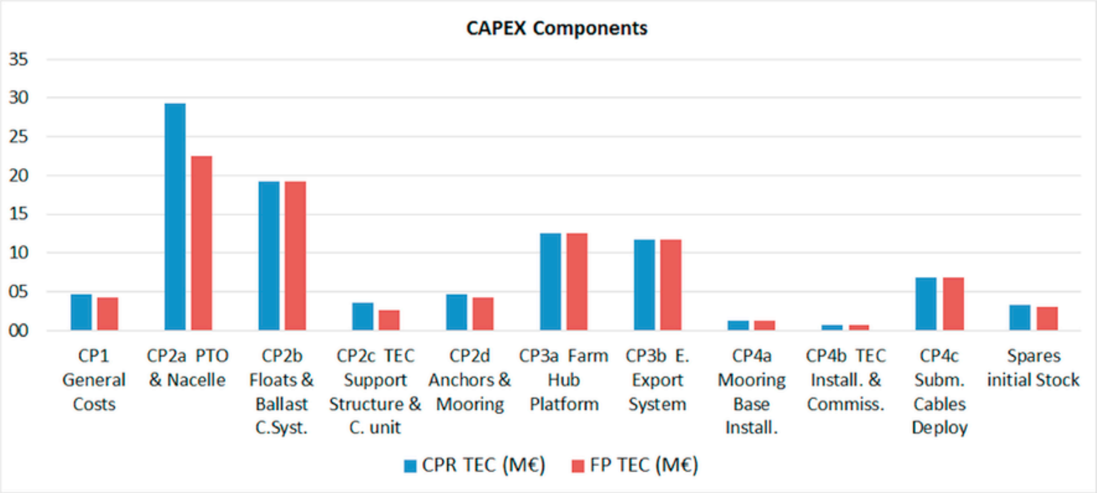


Fig. 12. Comparison between the main CAPEX components for the two alternatives.

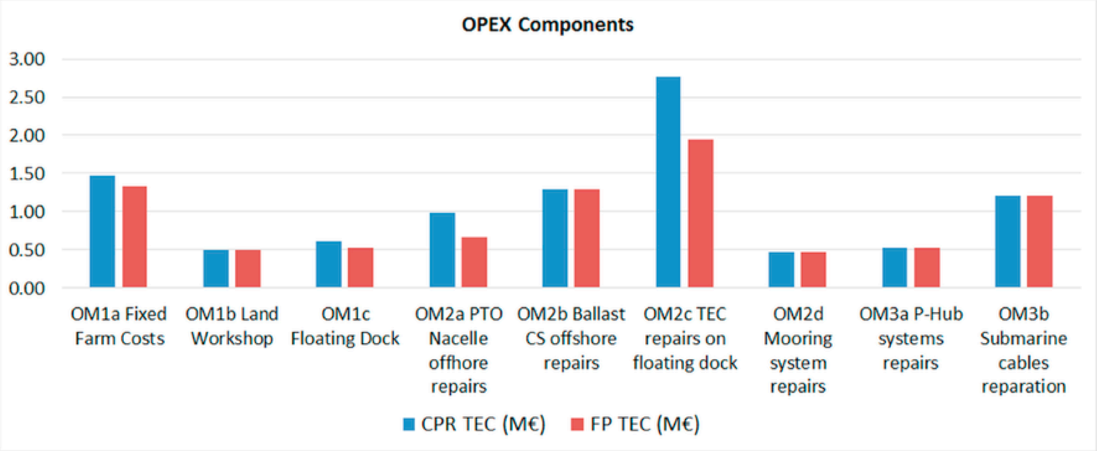


Fig. 13. Comparison between the main OPEX components for the two alternatives.

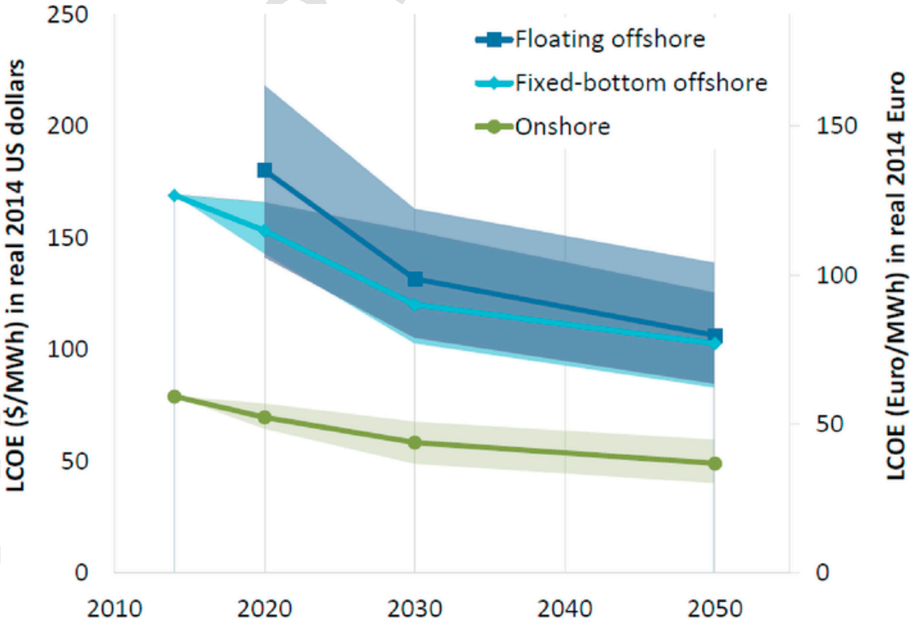


Fig. 14. Wind farms: LCOE reductions [50].

3.5. OPEX costs

The OPEX (acronym for Operation Expenses) mostly includes fixed costs such as insurance, leasing, support installations (docks, work-houses, etc.), operation personnel and, most importantly, the preventive and corrective maintenance costs.

As there is no real information regarding the maintenance costs of TECs, it is not possible to make a realistic calculation of the OPEX, and to this lack of actual figures must be added the difficulty involved in reaching the device, which may be restricted owing to the meteorological conditions (wind, waves and currents) in the area.

A previously developed model [28] circumvents the aforementioned difficulties by calculating the OPEX with the addition of four items, each of which is obtained as a percentage of a specific item of the CAPEX. This percentage was calculated using the actual Operation and Maintenance (O&M) information concerning offshore wind farms.

Other models in the field of tidal energy [46–48] make their estimations in relation to the probability of the access conditions combined with the probability of failure and repair times.

3.5.1. O&M model

The GITERM-UPM group is now working in this field to develop a model that will provide a detailed prediction of the costs of maintaining the farm by obtaining the expenses of the repair operations and foreseeing the TEC's non-operational periods caused by failures in the different devices. This method [49] is based on the reliability data for the main components and subsystems of the device, and on simplifying the mete-oceanic model and calculating the average window periods that are adequate to reach the array of TECs.

An operation protocol is defined for each repairing set, in addition to which human and material resources, such as the type of vessel used for the maintenance, are assigned. The size of the vessel defines the maximum wave height permitted, which, together with the weather conditions, make it possible to estimate the average waiting time for a convenient climate window. This waiting time, combined with the travel and repair time, is employed to define the Mean Time for Transport and Repair (MTTR). Once these times have been considered, it is possible to calculate the vessels and personnel costs needed for the repairs.

Moreover, the failure rate of the set can be calculated in relation to the reliability rates and the CAPEX contribution of the equipment comprising the set, which provides the Mean Time Between Failures (MTBF) and the cost of the spares needed.

The variable maintenance costs are obtained by integrating the cost items and the number of sets in the TEC array. Finally, the global availability can be calculated with the MTTR, the MTBF, the number of sets and their effect on energy generation.

This model is summarized in Fig. 10, in which a maintenance strategy is defined for each of the subsystems into which the device has been divided (sets). As an example, the GESMEY device has been divided into: Nacelle offshore repairs, Ballast CS offshore repairs, TEC repairs on floating dock, Mooring system repairs and P-Hub systems repairs. The strategy considers floating daytime repairs with the support of vessels based in a nearby harbour, and with a floating dock in that harbour for major repairs.

The starting point of the process described in Fig. 10 is the division of the device into sets and the definition of maintenance procedures that will configure the maintenance strategy. The steps established for this purpose are the following:

- Calculation of the failure rate using a reliability data base and obtaining the MTBF and its effect on the availability of the farm.
- Estimation of the cost of spares needed to carry out each repair.
- The MTTR for each set is obtained using the meteorological data, the maintenance procedures and the operative characteristics of the maintenance vessels.
- The cost of vessels and the technicians' salaries is also considered.
- Annual O&M costs are obtained by adding the different costs and the number of sets of which the farm is composed.

The fixed and preventive maintenance costs are obtained by using simpler models that are based on percentages of other costs or are attained by means of direct estimation.

3.5.2. O&M example

Table 11 shows the reliability results of the central nacelle, which needs more than 2.5 maintenance interventions per year, some of which can be carried out afloat by means of the set of operations scheduled in Table 12.; however, in some cases it may be necessary to tow the TEC to a floating dock (situated in the Cherbourg area) using the sequence shown in Table 13.

4. Model application to TEC GSY-1200-CPR and TEC GSY-1200-FP

The GESMEY-UPM group has developed a tool based on an Excel spreadsheet for the analysis of costs and LCOE, integrating extensive information that has been grouped in three cost concepts: manufacturing and assembly, oceanic installation operations, and operation and maintenance.

The aim of this section is to explain the model and spreadsheet results for the alternative of a TEC with controllable pitch. It will also provide a comparative study of the results obtained for both alternatives (fixed and controllable pitch).

Tables 14–16 show the data and results obtained for the GSY-1200-CPR, in which the "Base cost" column corresponds to data or functions predefined according to the parameters presented in Section 3 of this paper, and the "Value" column corresponds to data that must be introduced in each case, according to the proposed TEC design.

The OPEX data shown in Table 17 are obtained from a spreadsheet developed on the basis of the model explained in Section 3.

This model has been developed on a spreadsheet that includes the numerical values and the parameters, along with the efficiency of all the elements that participate in the energy generation, conversion and transport chain. This tool calculates the LCOE and provides an estimation of the costs, which can be used to compare alternatives and to carry out sensitivity studies that are not carried out in this paper owing to the high number of parameters to be taken in consideration.

The output summary of the spreadsheet developed for the GSY-1200-CPR is shown in Fig. 11.

In order to increase the clarity, the summary of the output has been split into three groups, (a), (b) and (c), and shown in Tables 18–20.

5. Discussion of the results

Bearing in mind the histogram of the currents in the Alderney Race and having performed the comparison between fixed pitch and controllable pitch, Table 21 shows an LCOE of 165 €/MWh obtained in the case of controllable pitch, while a much higher value of 204 €/MWh is obtained for the FP alternative.

It is clear that, although the CAPEX, OPEX and unavailability data for the fixed pitch are 9.2%, 13.9% and 7.7% less, respectively, when compared to those for the controllable pitch alternative, a much lower capacity factor signifies that the fixed pitch option has a 23.3% higher LCOE.

The most important output of this cost analysis method and of the tool developed is not only the resulting figures, but also the fact that it allows a detailed comparison of the different cost items. Figs. 12 and

13 show the comparison between the CAPEX and the OPEX for both alternatives, and it can be inferred that the cost of the item "PTO and Nacelle" is clearly much higher for the controllable pitch alternative, as is its effects on the maintenance costs, mainly as regards the in-dock repairs.

Please note that the model parameters are based on costs for a mature offshore wind technology and are not, therefore, directly applicable to the first farm built with this technology. In this a case, it would be necessary to increase the costs according to a learning curve. Furthermore, some of the items are highly changeable, such as the cost of renting vessels, along with other items that should be analysed in more detail, such as the hub platform.

Although there is clearly a wide range of uncertainty in future LCOEs, a relevant reduction in the LCOE is expected for offshore wind technology by 2050 (Fig. 14) [50], which makes it possible to predict a similar shrinkage in floating TECS.

An LCOE of 165 €/MWh for a TEC may seem high when compared to the LCOEs of offshore wind in recent tenders but, in addition to learning and scaling effects, there are still many drivers that can reduce this value, such as standardization, industrialization, electrical Balance of Plant (eBoP) optimization, operational synergies, low OPEX TECs, risk management, easier financing, etc. These could, in the medium term, lead to a competitive and highly predictable renewable energy technology.

6. Conclusions

The aim of this work has been to propose a cost model and tool for the calculation of the LCOE based on the design data of TECs and the general array type on a tidal energy farm. This model can be used in projects with low levels of TRL, while in parallel attaining high TPL levels.

The project presented here has involved the development of a generalist tool that integrates all the parametrized costs and that calculates the LCOE, among other variables. This tool has been applied to a single-rotor GESMEY-designed generator for the alternatives of both fixed and controllable pitch.

The numerical results of the model are, to a certain extent, inaccurate for several reasons, such as the current non-existence of commercial TECs in operation, the interrelation between the installation and maintenance costs and the geographical area, and the fluctuation in the cost of renting vessels.

The LCOE is, in this case, currently higher than that of other more mature renewable energies. This is partly compensated with the high long-term predictability of the resource, which will allow its integration into the electrical grid with considerable advantages. This LCOE is expected to be reduced in the future, as has already occurred in the offshore wind industry.

The GESMEY-UPM group is presently developing a detailed analytic model with which to calculate the OPEX that is linked to the analysis of the maintenance operations. The cost model, which has been developed on the basis of the parametrized costs and the various parameters selected, will make it possible to estimate the cost of the different devices. In addition to estimating the CAPEX, OPEX and LCOE, the model will also provide the possibility of comparing the results of different alternatives under different operation conditions in order to help the developer to choose the most convenient TEC at an early stage.

This paper shows the results obtained for the fixed and controllable pitch alternatives proposed. It is necessary to stress that the figures obtained depend on the design parameters selected, as the result could be different if other values were chosen for water speed, rotor diameter, etc. The tool presented allows the user to make comparisons for TECs other than those analysed in this paper and using different operation parameters. As a conclusion, the model presented in this paper is valid for the comparison of different design alternatives, under user defined operation conditions, for tidal energy projects in early TRL phases.

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