Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Life cycle and economic assessment of tidal energy farms in early design phases: Application to a second-generation tidal device

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ARTICLE INFO

Keywords:
Environmental impacts
Levelized cost of energy
Life cycle assessment
Marine renewable energy
Tidal energy

ABSTRACT

Ocean currents are emerging as key contributors to renewable energy generation. However, technologies for harvesting tidal current energy are still in the early stages of development. In this context, environmental and economic studies on tidal energy converters (TECs) are crucial to further advance tidal technology and facilitate its entry into the market. This article presents a life cycle and economic assessment of a 34.5 MW tidal farm project comprising 23 second-generation tidal devices, each with a rated power of 1.5 MW. The tidal system was simulated using primary data from the full-scale floating platform Atir. The Atir is a pre-commercial tidal device designed with a steel trimaran and a submerged section for TEC installation. An assessment of 18 environmental impact categories was conducted using the ReCiPe 2016 MidPoint method, with process flow systems modelled using SimaPro v9.2.0.1 software. The environmental assessment indicates emissions of 42.11 g CO2eq per kWh, primarily stemming from manufacturing processes that demand substantial amounts of steel. The economic analysis reveals a Levelized Cost of Electricity (LCOE) of 0.125 EUR/kWh, consistent with European Commission projections. Although the platform structure represents a high initial investment, the lower maintenance costs of the Atir device provide long-term savings and, overall, result in a competitive LCOE. The study also introduces a methodological framework for harmonised environmental and economic assessments in tidal energy projects, proving crucial in supporting decision-making processes.

List of abbreviations including units

AEP	Annual energy production
BOF	Basic oxygen furnace
CAPEX	Capital Expenditure
CR	Percent cost reduction
CTUe	Comparative Toxic Units ecotoxicity
EC	European Commission
EMEC	European Marine Energy Centre
EoL	End-of-Life
EPD	Environmental Product Declarations
EUR	Euro

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https://doi.org/10.1016/j.heliyon.2024.e32515
Received 12 February 2024; Received in revised form 3 June 2024; Accepted 5 June 2024

(*continued*)

FIT	Feed-in tariff
FoW	Fall of Warness
g	gram
GBP	Great British Pound
GHG	Greenhouse Gas emissions
GW	Gigawatt
GWP	Global Warming Potential
CO_2 eq	carbon dioxide equivalent
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
LCOE	Levelized cost of energy
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MW	Megawatt
MWh	Megawatt-hour
O&M	Operation and Maintenance
OPEX	Operational Expenditure
ORE	Ocean Renewable Energy
PEF	Product Environmental Footprint
PTO	Power take-off system
SA	Sensitivity analysis
USD	United Stated Dollar
TEC	Tidal energy converter
TEP	Tidal energy project

Nomenclature

A_s	Swept area of the turbine
C_p	Power coefficient
C_1	Total cost of the manufacturing phase
C_{11}	Total cost of the tidal device
C_{111}	Vessel manufacturing cost
C_{112}	Power take-off manufacturing cost (PTO)
C_{113}	Rotor manufacturing cost
C_{114}	Auxiliary system manufacturing cost
C_{12}	Mooring system cost
C_{13}	Electric system cost
C_2	Total cost of the installation phase
C_{21}	Cost of preparation prior to installation
C_{22}	Platform installation cost
C_3	Total cost of the operation phase
C_{31}	Preventive maintenance cost
C_{32}	Corrective maintenance cost
C_{33}	Insurance and fixed yearly expenses
C_4	Total cost of the decommissioning phase
C_{41}	Decommissioning cost of the platform electrical unhook
C_{42}	Uninstallation cost of the platform
C_{43}	Uninstallation cost of mooring system
C_{44}	Waste management and disposal
C_{45}	Incomes obtained from the secondary materials sales
C_{46}	Decommissioning cost project management
lc	Learning curve factor
LCC_{TEP}	Life cycle cost of tidal energy project
N	Number of tidal devices in the tidal farm
η_{AF}	Operational availability factor
η_{pes}	Efficiency performance power export system
η_{gr}	Efficiency performance generator
η_{gx}	Efficiency performance gearbox
P	Power turbine
P_d	Electrical power density
P_t	Theoretical power turbine
ρ	Seawater density
r	Discount rate
V	Free stream velocity

1. Introduction

Tidal current is currently considered to be one of the most promising green renewable energy sources to significantly contribute to energy supply [1]. Like wind turbines that use wind's kinetic energy, tidal turbines harness incoming and outgoing water flow energy, offering high predictability and overcoming intermittency issues in renewable energy. These advantages ease the integration of tidal energy into the electrical system, reducing operational uncertainties [2,3]. The global potential of tidal stream energy resources ranges from 64 GW to 120 GW [4]. In Europe, overcoming technological and financial barriers could pave the way for the announced projects to reach 600 MW in tidal stream energy within the next few years [5]. This aligns with the ambitious targets outlined in the EU offshore renewable energy strategy, aiming for 1 GW and 40 GW of ocean energy installed capacity by 2030 and 2050, respectively [6].

Despite the promising outlook, as of 2022, tidal energy's potential remains largely untapped. In Europe, cumulative installed tidal current capacity stands at 30.2 MW, with only 11.5 MW operational [7]. The slow progress in commercialising the tidal stream energy sector is attributed to a challenging investment landscape [5,8], characterised by high uncertainty about the reliability, feasibility and survivability of large-scale devices and arrays [9,10], as well as a limited understanding of the environmental impacts generated [11, 12].

Existing life cycle assessment (LCA) studies heavily rely on assumptions and tend to focus primarily on carbon emissions [13], neglecting a more holistic evaluation of environmental impact categories. Similarly, the absence of a standardised economic assessment approach poses challenges in making consistent comparisons among studies, highlighting the necessity for a uniform and comprehensive methodology [9]. Any renewable energy system intended for commercialisation must undergo an economic assessment to establish a comprehensive quantification of its costs [20]. This evaluation is crucial to verify the system's profitability, attract investments, and facilitate its commercialisation [21]. However, the limited experience in evaluating tidal energy projects poses challenges, as there is a current scarcity of data and a high level of uncertainty [13,22]. Furthermore, existing economic studies generally neglect the estimation of economies of scale and how they might impact the commissioning of tidal parks, a critical factor for the commercialisation of tidal energy technologies. Finally, studies combining LCA and economic assessments are lacking, thus limiting an in-depth understanding of potential trade-offs or synergies in tidal energy projects.

This study addresses these research gaps by presenting a joint life cycle and economic assessment of a 34.5 MW tidal energy array based on the Atir full-scale prototype [14], the Magallanes' tidal device that has been operating since March 2019 at the Fall of Warness tidal test site in Orkney (UK). The assessment was conducted as part of the EU project 'Next Evolution in Materials and Models for Ocean Energy' (NEMMO[1]). The novelty of the proposed research is twofold. First, we present a modern tidal technology that has not yet been the subject of environmental or economic analysis. Due to the advanced stage of development of the Atir platform, both assessments are based almost entirely on primary data provided by the manufacturer, including the costs used for the economic analysis. Second, by presenting a joint LCA and economic assessment, we introduce a modular and comprehensive framework for conducting these analyses consistently. Drawing on state-of-the-art literature, both assessments enhance existing knowledge by incorporating a diverse set of environmental indicators and exploring a parametric approach to tackle economies of scale.

The paper is structured as follows: after this introduction, Section 2 outlines the main features of the Atir device, including its expected annual energy production. Section 3 details the system boundary, primary data and indicators used for the LCA and economic assessment, including methodological steps, key assumptions and technical parameters. The results of the case study are presented and discussed in Section 4 and Section 5, respectively. Section 6 summarises the main results, providing policy implications and offering recommendations for future work.

2. Technical description of the tidal device

Fig. 1 shows a schematic view of the Atir device comprising a steel platform (upper block) connected to a submerged part (lower block) where the hydrogenators are positioned. The 45-m platform is equipped with two 21-m-high counter-rotating three-bladed rotors situated below the hull, collectively attaining 1.5 MW rated power. Since the platform floats, there is no construction on the sea bottom. In addition, the tidal device is designed so that most maintenance or repair can be done from inside the platform, providing access to the machinery room 15 m below sea level.

The upper block is divided into three main rooms: one room is allocated to pumps and emergency power systems, whereas the other two rooms have been designed for accommodating the transformers, converters, switchgears, and electrical panels, in addition to other parts of the electrical and electronic systems. In addition to these three main rooms, there are two inaccessible compartments at either end of the block that are part of the ballast system. This uses treated fresh water, as well as several tanks in the centre of the block to supply environmentally acceptable lubricant and bilge water.

The lower block hosts the mechanical system. The most relevant components placed in this block are the main shafts, ball bearings, gear boxes and generators. As indicated before, the platform is fitted with two counter-rotating rotors. As a result, all components of the mechanical system are duplicate (one for each rotor). Fig. 2 provides a schematic overview of the mechanical system situated in the lower block.

The platform is anchored to the sea bottom by four mooring lines, two in the bow and two in the stern. Each anchor point consists of a steel chain catenary leg, fixed to a hull attachment point at the bow and stern. The mooring system holds the platform in line with the

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[1] https://nemmo.eu/.

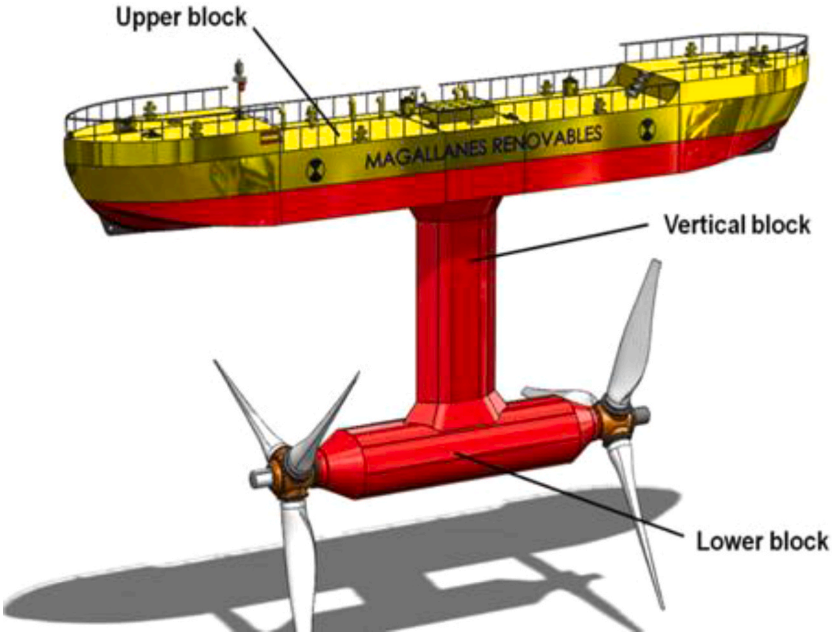

Fig. 1. Schematic view of Atir tidal device.

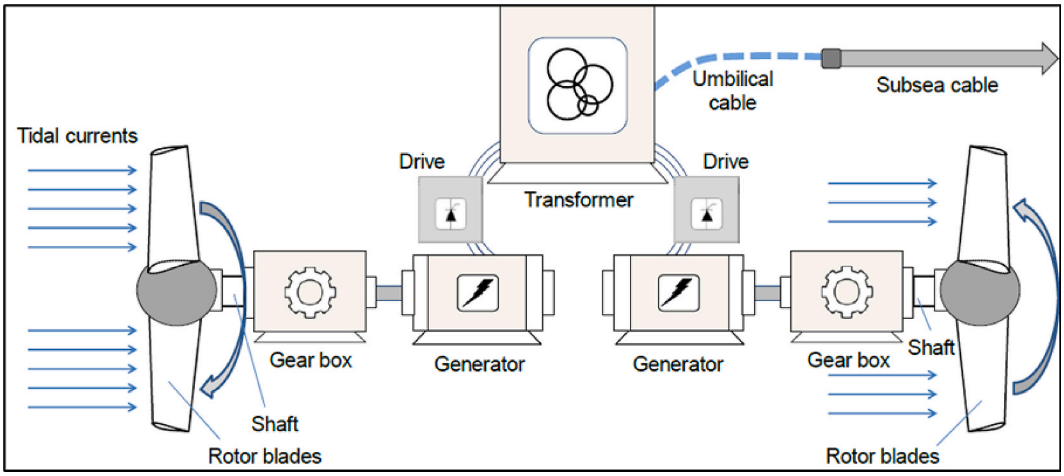

Fig. 2. Diagram of the main components of the mechanical system.

current flow. The total length of the mooring lines of each platform is 395 m (x4) and the total weight of the mooring lines of each platform is 762 tonnes, with an expected lifetime of 25 years.

Once moored, tidal currents turn the blades of the two counter-rotating rotors, which are operational at the same time. The blades have a variable pitch system to allow blade configuration and pitch to change according to the current. The movement of the blades produces the spinning of a shaft and, subsequently, by means of a generator, the mechanical energy is converted into electricity. A power transformer increases the voltage so as to reduce energy losses during power take off.

Finally, the electricity generated by each tidal device is transmitted through the umbilical cable (33 kV cable) to the connector (150 m for each tidal device). From the connector, the EMEC static array cable (132 kV cable) connects to the shore-based substation for onward transmission to the National Grid (3.5 km distance to the shore).

2.1. Annual energy production

The Annual Energy Production (AEP) describes the average annual energy generated and delivered to the point of grid interconnection. The AEP is a critical indicator for decision-making during the installation of a tidal farm as it is required to calculate the

LCOE (cfr. EQ. (5)), as well as to normalise environmental impacts (see Section 4.1). The International Electrotechnical Commission (IEC) has published a technical specification for performing tidal stream energy resource assessments for projects at both feasibility and design stages [15]. The theoretical power available for an individual turbine is computed as a cube of the free stream velocity $P_t = \frac{1}{2}\rho V^3$, where ρ is the density of the water and V the flow speed. In order to account for the efficiency of a particular turbine, the equation can be modified by introducing the performance power coefficient C_p:

$$P_d = \frac{1}{2} C_p \rho V^3 \qquad \text{EQ. 1}$$

Where P_d is the electrical power density. In general, C_p upper bound (59.3 %) for turbines in an unconstrained flow is derived using actuator disk theory and is formally referred to as the Betz limit [16]. Even if this approach was performed for wind turbines, it is generally accepted that it also applies to tidal energy, providing the turbine swept area is small relative to the channel depth and width as in this case [17]. The actual electricity power output also depends on the properties of the turbine. In this sense, the power for the turbine (P) is found by multiplying the power density (P_d) by the swept area of the turbine, A_s:

$$P = \frac{1}{2} C_p \rho V^3 A_s \qquad \text{EQ. 2}$$

When assessing the total energy produced several additional requirements need to be considered in order to estimate a realistic value of the total energy. These are.

- The operational availability factor η_{AF}, which defines the actual time a turbine is working and producing energy. This availability factor is estimated on the basis of the information obtained from the maintenance procedures used, weather windows, and so on. The reader can refer to the supplementary material, section 2.3.4. “operational availability of the tidal device” for a detailed description on how it was assessed.
- Efficiency performance of the gearbox (η_{gx}), generator (η_{gr}) and power export system (η_{pes}). Values for η_{gx} generally range from 92 % to 96 % [18], while values for η_{gr} can range from 90 % for smaller generators to 98 % for larger generators [18]. Values for η_{pes} have been found to range between 95 % and 98 % [9,18]. In this study, the values of η_{gx} , η_{gr} and η_{pes} (Table 1) refer to the manufacturer’s technical specification and were provided by Magallanes within the EU NEMMO project framework.

As a result, the AEP can be estimated by the following formula:

$$AEP = \eta_{AF} \frac{8766}{1000} \eta_{gx}\eta_{gr}\eta_{pes}\frac{1}{2} C_p \rho V^3 A_s \qquad \text{EQ. 3}$$

Where 8766 is the number of hours in a Julian year (365.25 days), and 1000 is the number of Watts (W) per kW. AEP is expressed in units of kilowatts-hours (kWh). Table 1 presents the input parameters employed to calculate the AEP. AEP for a single tidal device is equal to 4104 MWh. For the calculation of the total AEP’s farm, we assumed equal inflow conditions (and available power density) for all devices in the array. Therefore, the AEP estimate for an array was the AEP for a single device multiplied by the number of devices. This assumption clearly overestimates the AEP for an array, but in this case, given the early-design phase of the study, the velocity deficit due to different rows of tidal devices was considered negligible overall.

Table 1
Input parameters for AEP estimation.

Input parameters	Value	Unit	Source
Turbine diameter	21	m	Magallanes
Turbine Swept area (As)	346	m2	Own estimation
Power coefficient (Cp)	0.52	%	Magallanes [14]
Water density (ρ)	1.025	Kg/m3	
Free stream velocity (annual average) (V)	1.50	m/s	Orkney (Scotland, UK)
Operational availability factor (η_{AF})	84.5	%	Own estimation based on turbine downtime due to preventive and corrective maintenance (see SI for calculation)
Coef. performance of the gearbox (η_{gx})	0.96	%	Manufacturer
Coef. performance of the generator (η_{gr})	0.98	%	Manufacturer
Coef. performance of the export system (η_{pes})	0.95	%	Manufacturer
AEP single tidal device	4104	MWh	Own estimation (EQ. (3))

3. Material and methods

3.1. Life cycle assessment

The LCA methodology is structured according to the ISO 14040:2006 framework and it includes (1) goal and scope definition, (2) inventory analysis, (3) life-cycle impact assessment, and (4) interpretation. (1) The goal and scope definition mainly includes setting the objectives of the study, selecting the assessment parameters, deciding the functional unit, and defining system boundary; (2) the inventory analysis compiles information about the physical flows in terms of input of materials and energy and the output of emissions, waste and valuable products for the system boundary. The flows are scaled in accordance with the reference flow of product that is determined from the functional unit; (3) the life-cycle impact assessment (LCIA) translates the physical flows into environmental impacts through three main sub-steps: First, by selecting impact categories for analysis. Second, by assigning the life cycle inventory results to different impact categories (classification). Third, by calculating the potential impact indicators (characterization). (4) The interpretation of the inventory and impact assessment results is performed to answer the objectives of the study and the questions posed as part of the goal definition.

3.1.1. Goal and scope definition

The goal of this LCA is to investigate the environmental impacts of electricity generation from the tidal energy array consisting of 23 platforms of 1.5 MW each, based on the Atir tidal device. In this context, the functional unit used as a common reference is one kWh of electricity produced by the tidal system and delivered to the grid connection point. Fig. 3 shows the system boundary considered in this LCA. The system boundary has been defined following the recommendations given by the Product Category Rules [36] developed within the International EPD® System framework [19]. In this line, this LCA applies a “cradle-to-gate” approach including.

- Upstream module**,** which includes the environmental impacts related to the production of all auxiliary substances necessary for the smooth operation of the tidal farm during its lifetime, such as lubricating oil and antifouling paint, as well as the emissions from the transport of these substances from the suppliers to the tidal energy farm.
- Core module (I): *infrastructure*, which covers all stages related to the construction and decommissioning of the tidal energy farm. Namely, the extraction of the raw materials necessary for the construction of the tidal devices, mooring systems and electrical systems, and the dismantling of the tidal farm, including the correct management of the waste generated and the recycled components, as well as their corresponding treatment at the end of their useful life.
- Core module (II): *operation*, which addresses all environmental impacts associated with the operation of the tidal energy farm throughout its lifetime. Namely, the preventive maintenance required during the lifetime of the farm, including the travel of maintenance personnel to the tidal energy farm, as well as the management of waste consumables required during the operation and maintenance of the tidal energy platforms.

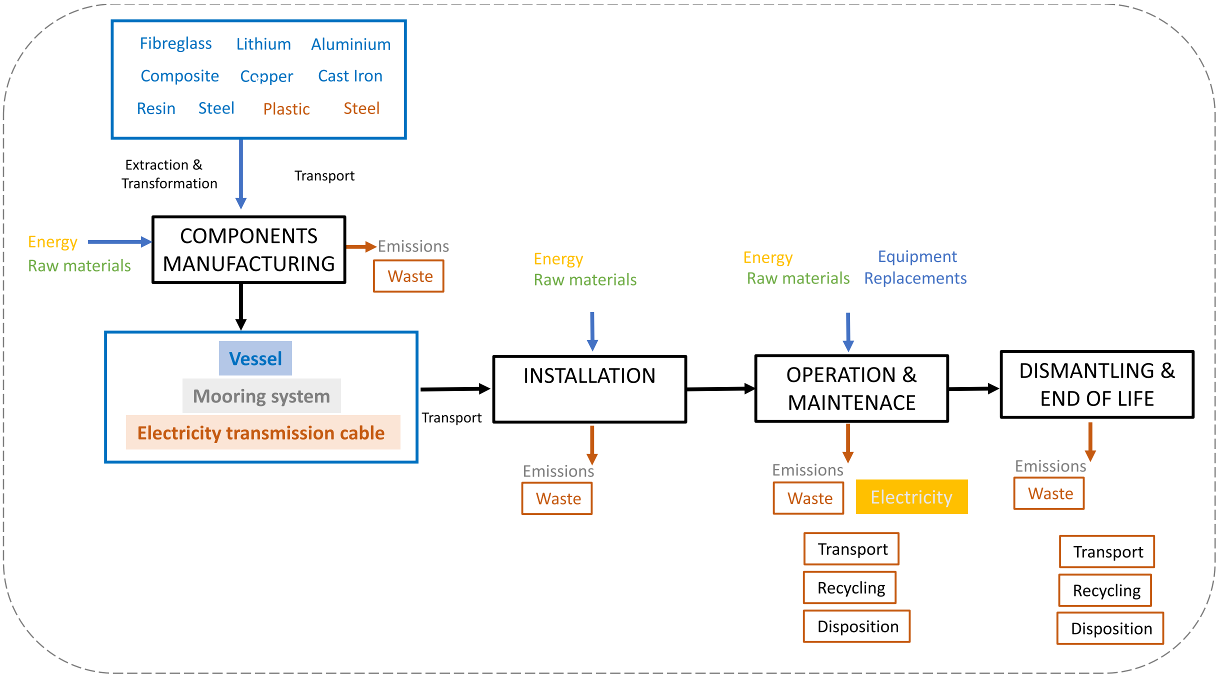

Fig. 3. System boundary for the LCA.

The downstream module is not considered in this study. Therefore, all impacts that occur from the moment the energy is injected into the electricity grid until it reaches the final consumer are excluded.

3.1.2. Life cycle inventory (LCI)

Two types of data were considered in the inventory: primary and secondary data. Primary data, which was obtained from Magallanes, was used to characterize the core modules. Secondary data, which was retrieved from specialised databases such as Ecoinvent v3.9.1 [20], was used to characterise the upstream processes (extraction of raw materials) and end-of-life scenarios. The SimaPro v9.2.0.1 software was used to model the system.

The inventory was organised according to the life-cycle stages and, respectively, main components of the tidal system (Fig. 3). These are: 1) the manufacturing of the tidal energy farm, which includes the tidal device (i.e., platform, PTO, rotor and auxiliary system), the mooring and electrical systems; 2) the installation of the tidal system components; 3) the activities related to operation and maintenance, including auxiliary substances necessary for the operation of the tidal farm and 4) the activities related to decommissioning and dismantling, including EoL treatment of waste. The lifespan of all components is 25 years, except for some auxiliary components, which must be periodically replaced. Table 2 describes the main materials, and respective weights, for the main tidal farm components that have been modelled in the LCA, while Table 3 details the EoL scenarios approach considered within the LCIA for each component.

Table 2
Main components of one 1.5 MW-Atir tidal device.

Tidal system component		Subcomponent	Main materials	Tonnes per platform (2 turbines) 1.5 MW
Atir tidal device	**Platform**	Vessel structure	Steel	360
		Ballast	Steel	45
	Power Take-Off (PTO)	Gearbox	Clean steel	27.9
		Generator	Steel, copper, cast iron and aluminium	8.7
		Transformer	Aluminium, copper and steel	6
		Converter	Aluminium, copper and steel	4.4
		Brakes	Steel	0.1
	Rotor	Blades	fibre glass reinforced polyester (56 %) vinyl ester resin (39 %), gel coat (1 %) and adhesive (3 %).	12
		Variable Pitch system	Steel, fiberglass, cast iron, copper, and aluminium	58.16
		Main shaft	Steel, cast iron	27
		Bearings	Steel	2.7
		Oil tank	Steel	1
	Auxiliary System	Genset	Steel, copper, composite, aluminium	0.4
		Fuel Tank	Aluminium	1
		Fire extinguisher system	Steel, composite	1
		Hydraulic system	Steel, copper, aluminium, composite	0.2
		SAI	Steel, lithium, copper, aluminium	0.45
		Cells	Steel, copper, aluminium	0.28
Mooring system	**4-point mooring system**	Chain and fixing system	Steel	762
Electrical system	**Cable**	133 kV cable	Steel, copper, lead, polyethylene and polypropylene	4.35
		33 kV cable	Steel, copper, lead, polyethylene and polypropylene	13.54

Table 3
End-of-life scenarios for tidal farm components.

Material	EoL scenario	Comments
Gearbox (100 % clean steel)	100 % recycling	
Generators (40 % cast iron, 25 % Cu, 25 % Al, 10 % steel)	100 % recycling	All the materials may be recycled
Blades (56 % fiberglass + 39 % resin)	100 % landfilling (fiberglass + resin)	
Variable Pitch system (90.5 % Steel, 9.5 % others (fiberglass, cast iron, Cu, Al))	90.50 % recycling	90.5 % of steel gets recycled
Main shaft (99 % Steel, 1 % cast iron (coating))	99 % recycling	
Platform (100 % steel)	100 % recycling	Lifting of the platform to the quay and scrapping. Steel is then recycled.
Mooring system (line) (100 % steel)	100 % recycling	De-installation of the mooring system, removal from site to wet storage. Steel from mooring lines is recycled.
Ballast (100 % steel)	100 % recycling	
Cables (steel 36 %, copper 25 %, lead 25 %, polyethylene 9 %, polypropylene 5 %).	36 % + 25 % recycling	Copper and lead get recycled. The remaining components are landfilled

3.1.3. Life cycle impact assessment and modelling assumptions

The ReCiPe 2016 methodology at a midpoint level with a Hierarchist perspective was used for the impact assessment [21]. This evaluation method was chosen because it has been widely used by other authors in other LCA studies of tidal energy systems [22–24]. The method considers 18 impact categories, each of which is measured with a specific unit. Of these, four impact categories were considered the most relevant for the purpose of this study and were therefore assessed in greater detail. These are: global warming, marine eutrophication, marine ecotoxicity and water consumption. Greenhouse gas (GHG) emissions represent a serious global problem, and their reduction is one of the main objectives pursued by the use of renewable energy. GHG quantification is carried out through the Global Warming impact category, and the unit of measurement is kg CO2eq. Marine eutrophication is caused by the run-off and leaching of plant nutrients from the soil, and their discharge into river or marine systems. Marine eutrophication produces an increase in the concentration of nutrients in the water (phosphorus and nitrogen) and its impact is measured in kg N eq. Marine ecotoxicity measures the toxic effects produced by additional inputs of essential metals (cobalt, copper, manganese, molybdenum and zinc) into the oceans. The unit of measurement for this category is kg 1,4-DCB. Finally, water consumption represents the amount of water consumed, both directly and indirectly. It is quantified in m3 of water [21].

To ensure a comprehensive analysis of the environmental performance of this technology, the material and energy inputs excluded from this LCA do not represent more than 3 % of the cumulative mass of the core system. This cut-off criterion is in line with the recommendations given by the European Commission in the Product Environmental Footprint (PEF) methodology guide [25]. Regarding system multifunctionality issue, it was considered that the electricity is the only product generated by the process under study. Therefore, all the impacts generated by the production process have been attributed to the generated electricty. Regarding the end-of-life stages of the tidal farm, the polluter pays principle has been applied as “allocation rule” for assigning environmental impacts related to waste [26]. This means that those who generate the waste and pay for its management bear the environmental impact until the moment the waste changes ownership, i.e. when it is transferred to a waste treatment plant (or landfill). Hence, no credits (negative flows) have been considered as an outcome based on recycling rates when modelling the EoL stages of marine park infrastructure.

3.2. Economic assessment

Economic assessment refers to the evaluation of financial and economic performance of a project or technology and it is used to inform developers, sponsors, or policy makers about the financial viability of specific projects or technologies [27,28]. This kind of economic assessments are typically based on the evaluation of the levelized cost of energy (LCOE). The LCOE is a fundamental economic parameter that represents the cost per unit energy produced over the lifetime of a turbine or a farm. In addition to the LCOE, economic assessments often provide insights into the overall distribution of costs, typically expressed as percentages or in million euros per installed capacity (M EUR). Capital expenditures (CAPEX) and operational expenditures (OPEX) serve as the primary macro-economic cost categories for comparing various tidal devices.

In this study, the economic approach used to assess the LCOE is based on the life cycle costing (LCC) approach proposed by Segura et al. [9]. The authors provided a modular accounting structure that organises and connects activities related to the construction, installation, operation and decommissioning of a tidal park. In this context, these modules also mirror the life cycle of the tidal farm, aligning seamlessly with the LCA system boundary presented earlier. Fig. 4 shows the life cycle stages included in the economic

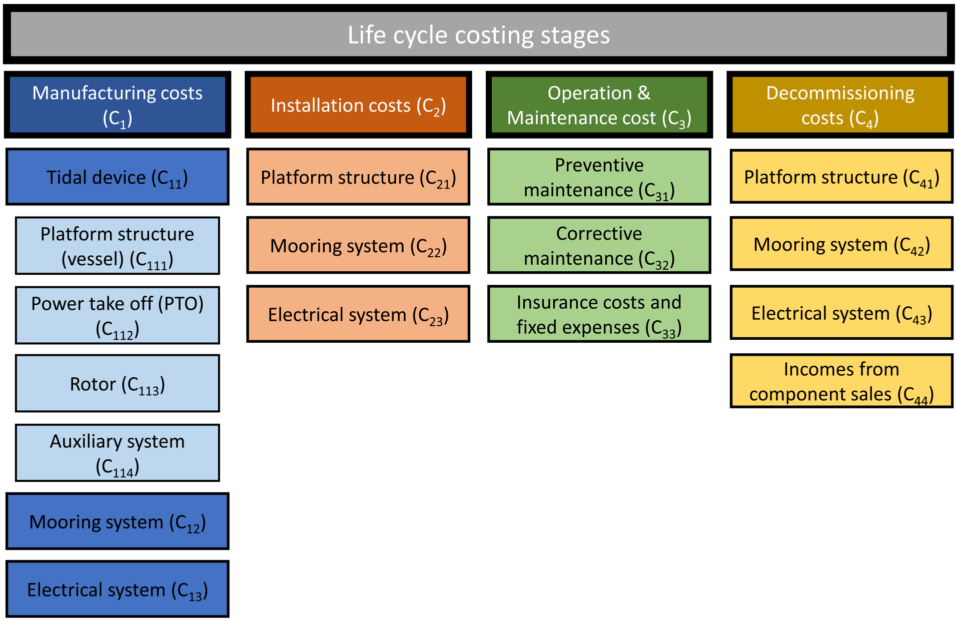

Fig. 4. Life cycle costing stages and components included in the economic assessment.

assessment, including respective components. Mathematical expressions for calculating each component are available in the supplementary material. These were developed by considering existing approaches from the literature and the primary data gathered for this study. Additionally, we employed a parametric approach to quantify the cost reduction resulting from commissioning a greater number of components. Magallanes' field experience served as a valuable counterpoint to both the cost model and the economies of scale-induced cost reduction.

Once that costs for each life cycle stage have been computed, the total life cycle cost of a tidal energy projects (LCC_{TEP}) can be expressed as:

$$LCC_{TEP} = C_1 + C_2 + C_3 + C_4 \qquad \text{EQ. 4}$$

Where C_1 is the total cost of the manufacturing phase, C_2 is the total cost of the installation phase, C_3 is the total cost of the operation and maintenance phase and C_4 is the total cost of the decommissioning phase. For the complete model, including lower-level mathematical expressions, the reader can refer to the supplementary material.

Economic results were analysed by means of the following indicators: Capital Expenditure (CAPEX) Operational Expenditure (OPEX) and the Levelized Cost of Energy (LCOE).

- CAPEX refers to those expenditures whose benefits extends beyond one year. Typically, capital expenditures include the investments required to build and prepare the tide park for operation such as the cost of the power take-off, the support structure of tidal devices, the mooring and electrical systems, among others [29]. From a lifecycle perspective, these generally occur during the manufacturing and installation phases [9].
- OPEX refers to those expenses necessary to keep the tidal park running, including required expenses to guarantee efficient operation. These includes insurance costs, operation and maintenance (preventive and corrective) costs and payments for rent, among others [29]. Due to unpredictable weather conditions, which affect maintenance and operating costs, and the lack of historical data on maintenance of full-scales devices and device arrays, OPEX values are generally characterised by a high uncertainty.
- LCOE can be defined as the life-cycle cost divided by lifetime energy production. Mathematically:

$$LCOE = \frac{C_{CAPEX} + \sum_{t=1}^{n} C_{OPEX_t} \cdot (1+r)^{-t}}{\sum_{t=1}^{n} AEP_t \cdot (1+r)^{-t}} \qquad \text{EQ. 5}$$

Where C_{CAPEX} denotes the CAPEX, C_{OPEX_t} expresses the OPEX in year t, and AEP_t represents the Annual Production of Energy in years t expressed in kWh, r is the interest rate and t is the time (in years) during which the tidal farm is exploited. LCOE is a convenient metric 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 investments and time operations.

Finally, the sensitivity and uncertainty of the LCOE metric to most sensitive parameters have been investigated to determine the reliability of our results.

3.2.1. Economic inventory and learning rates

The economic assessment mainly relies on primary data supplied by Magallanes. This data encompasses both technical and economic information and is derived from the operation of the Atir full-scale prototype since March 2019 at the Fall of Warness tidal test site in Orkney,[2] UK (Fig. 5). Therefore, it represents the most accurate information available as of 2023.

In order to assess the total life cycle cost of the tidal array specific learning rates have been applied to account for, *inter alia*, economies of scale. Learning rates can be defined as the fraction of cost reduction per doubling of installed capacity and are commonly used to describe the potential reduction in cost of energy generation brought by learning [3] (i.e., if producing the first MWh of energy costs EUR 100 and the second MWh costs EUR 90, the learning rate is 10 %). The learning rate formula used for the economic assessment of this case study is based on EQ. *6* [30]:

$$CR = N^{\left(\frac{\ln(lc)}{\ln(2)}\right)} \qquad \text{EQ. 6}$$

Where CR is the percent cost reduction for each additional unit calculated as a function of the number of tidal devices N and the "learning curve" factor *(lc)*.

Table 4 presents an overview of the main costs' elements referred to the Atir device, along with respective learning curve factors. Due to confidentiality reasons, the economic evaluation for each single element has been removed. For a detailed description of the technical equipment included in each cost element and calculation approach, the reader can refer to the supplementary material.

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[2] https://www.emec.org.uk/about-us/our-tidal-clients/magallanes-renovables/.

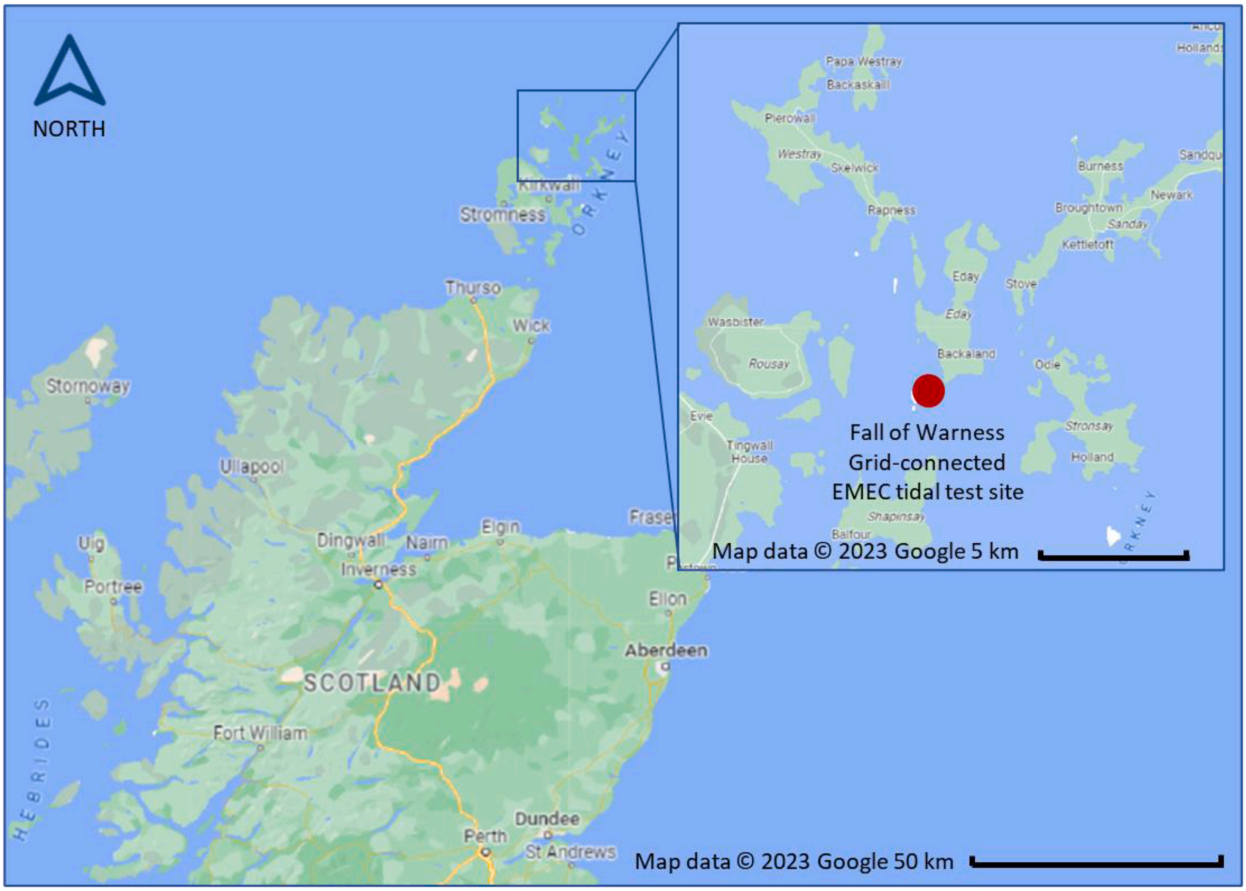

Fig. 5. Location map of the offshore tidal device test area.

Table 4
Economic inventory for a single tidal device.

Abbreviation	Component	Learning curve factor (lc)
C_{111}	Vessel manufacturing cost	0.93
C_{112}	Power take-off manufacturing cost (PTO)	0.93
C_{113}	Rotor manufacturing cost	0.93
C_{114}	Auxiliary system manufacturing cost	0.93
C_{12}	Mooring line cost	0.93
C_{13}	Electric cable cost	0.93
C_{21}	Cost of preparation prior to installation	0.93
C_{22}	Platform installation cost	0.93
C_{31}	Preventive maintenance cost	0.95
C_{32}	Corrective maintenance cost	0.95
C_{33}	Insurance and fixed yearly expenses	–
C_{41}	Decommissioning cost of the platform electrical unhook	0.93
C_{42} U	ninstallation cost of the platform	0.93
C_{43}	Uninstallation cost of mooring system	0.93
C_{44}	Waste management and disposal	0.93
C_{45}	Incomes obtained from the secondary materials sales	–
C_{46}	Decommissioning cost Project management	0.93

4. Results

4.1. LCIA results

Table 5 presents the environmental impacts generated for each kWh of electricity produced according to the 18 impact categories included in the ReCiPe 2016 Midpoint (H) method. Fig. 6 shows the relative distribution of the impacts across the different tidal system components and for the most relevant impact categories for the system under study.

Considering the climate change impact category, 42.11 g of CO_2eq are generated for every kWh of electricity produced. In general, most of the selected impacts are generated by the manufacturing of the tidal farm's equipment. In particular, the manufacturing of the

Table 5
Environmental impacts per kWh produced in the 34.5 MW tidal energy farm.

Impact category	Units	Value (per MWh)
Global warming*	kg CO_2 eq	4.21E-02
Stratospheric ozone depletion	kg CFC11 eq	1.20E-08
Ionizing radiation	kBq Co-60 eq	4.66E-03
Ozone formation, Human health	kg NOx eq	1.11E-04
Fine particulate matter formation	kg PM2.5 eq	7.12E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.17E-04
Terrestrial acidification	kg SO_2 eq	1.44E-04
Freshwater eutrophication	kg P eq	3.14E-05
Marine eutrophication*	kg N eq	2.96E-06
Terrestrial ecotoxicity	kg 1,4-DCB	3.27E-01
Freshwater ecotoxicity	kg 1,4-DCB	2.25E-02
Marine ecotoxicity*	kg 1,4-DCB	2.81E-02
Human carcinogenic toxicity	kg 1,4-DCB	8.17E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	1.54E-01
Land use	m^2a crop eq	1.19E-03
Mineral resource scarcity	kg Cu eq	1.21E-03
Fossil resource scarcity	kg oil eq	1.03E-02
Water consumption*	m^3	2.63E-04

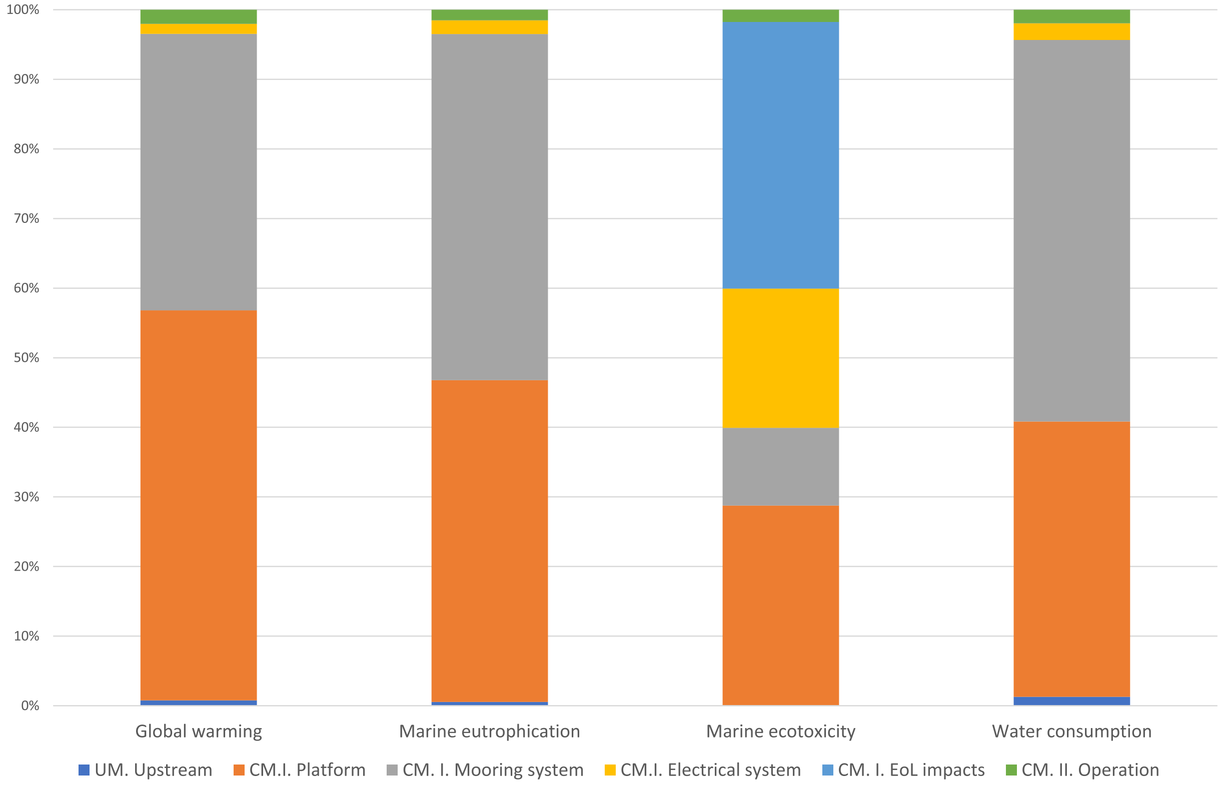

Fig. 6. Relative environmental impact per kWh of electricity produced in the 34.5 MW tidal energy farm.

Table 6
Environmental impact generated by the manufacturing of the Atir tidal device components per kWh.

Impact category	Units	Total	Vessel structure	PTO components	Rotor system	Auxiliary Systems
Global warming	kg CO2 eq	2.36E+01	1.70E+01	2.34E+00	3.91E+00	2.96E-01
Marine eutrophication	kg N eq	1.37E-06	9.56E-07	1.41E-07	2.60E-07	1.21E-08
Marine ecotoxicity	kg 1,4-DCB	8.07E-03	1.82E-03	3.76E-03	2.26E-03	2.24E-04
Water consumption	m3	1.04E-04	5.86E-05	1.60E-05	2.74E-05	2.04E-06

tidal device is the major contributor in the global warming category, representing 56 % of the total GHG emissions. On the other hand, the manufacturing of the mooring system is the main driver of impacts related to marine eutrophication and water consumption indicators (50 % and 55 %, respectively), with the impact of platform construction also being very significant in both categories (46 % and 40 %, respectively). Differently, the impact category of marine ecotoxicity shows a different behaviour since most of the impacts are produced during the EoL phase (38 %). This is due to the management of tidal farm components (mainly metal structures) at the end of their useful life.

Table 6 and Fig. 7 provides numeric results and relative distribution of environmental impacts generated by the manufacturing of the Atir tidal device according to its main components. Looking into the global warming indicator, the total CO_2 emissions caused by the different components of a tidal device are distributed as follows: vessel structure (72 %), rotor system (17 %), PTO components (10 %) and auxiliary systems (1 %). The reason for this impact distribution is the huge amount of steel that is needed to build the structure of the vessel. Primary steel was assumed to be produced in a basic oxygen furnace (BOF), in a discontinuous process, involving the following steps: 1) pre-treatment of hot metal (pig iron), 2) alloying, weighing, and reloading, 3) oxidation in the BOF, 4) secondary metallurgical treatment in a ladle furnace and 5) casting. Besides, a content of around 20 % of secondary raw material (iron scrap) was considered to simulate the impacts of the low-allowed steel.

Regarding the remaining impact categories, the steel production needed to manufacture the vessel structure also represents the most significant driver in other environmental categories. Concretely, it generates 70 % of the total marine eutrophication impact caused by the entire platform, and 56 % of the total impact measured with the indicator water consumption, Finally, the vessel structure also generates 23 % of the total marine ecotoxicity of the Atir tidal device, although in this case, the copper elements included in the PTO components are the main cause of impact (47 %).

Regarding the rest of the impacts caused by the PTO components, the construction of the gearbox is the part that generates the highest impact on the Global warming (51 %) and marine eutrophication (50 %) indicators. On the other hand, the generator is the component of the PTO system with the greatest environmental impact on the marine ecotoxicity and water consumption indicators (81

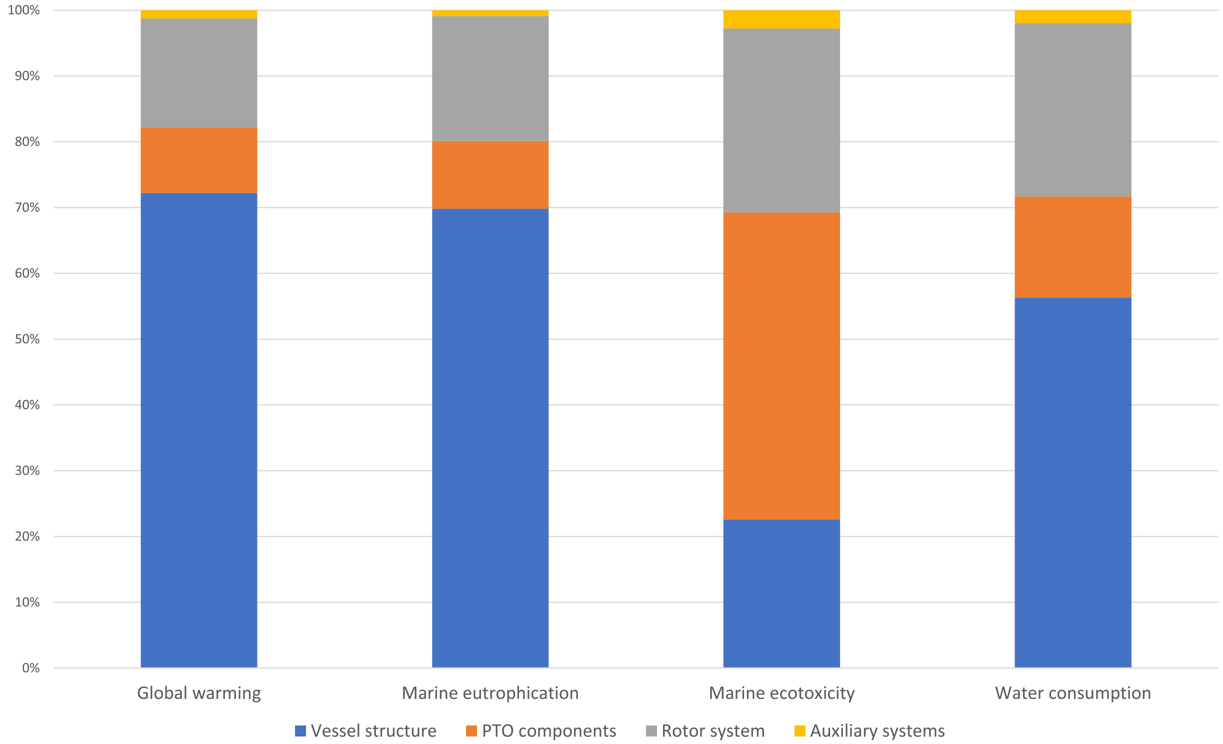

Fig. 7. Environmental impacts generated by the manufacturing of Atir tidal device.

Table 7
Environmental impacts of the mooring and cable system.

		Mooring system	Electrical system			
			132 kV cable		33 kV cable	
Impact category	Units	Impact/kwh	Impact/kwh	Impact/m	Impact/kwh	Impact/m
Global warming	g CO2	1.67E+01	4.57E-01	3.12E+05	1.45E-02	9.79E+04
Marine eutrophication	kg N eq	1.47E-06	4.48E-08	3.06E-02	1.36E-09	9.19E-03
Marine ecotoxicity	kg 1,4-DCB	3.14E-03	4.32E-03	2.95E+03	1.26E-04	8.53E+02
Water consumption	m3	1.44E-04	4.81E-06	3.29E+00	1.49E-07	1.01E+00

Table 8
Other life cycle impacts of the tidal energy farm, per kWh.

Impact category	Units	Upstream Module	Operation	EoL
Global warming	g CO2 eq	3.27E-01	4.58E-02	2.83E-03
Marine eutrophication	CTUe	1.60E-08	1.44E-09	1.02E-10
Marine ecotoxicity	Pt	1.99E-05	4.80E-06	1.08E-02
Water consumption	m3 depriv.	3.34E-06	1.21E-07	4.95E-08

% and 32 % respectively. Finally, with respect to the rotor system, the variable pitch system is the component generating the highest environmental burden across all indicators selected, as its relative weight ranges from 54 % of the total impact for the water consumption indicator to more than 93 % for the marine ecotoxicity indicator.

In order of magnitude, after the manufacture of the tidal device, the elements of the tidal system with the greatest environmental impact are the mooring and electrical system. These are showed in Table 7. The mooring system, which includes four steel anchor lines per platform for a total weight of 762 tons, produces 16.73 g of CO_2 emissions per kWh. Again, steel production is the main driver of environmental impacts. It follows the electrical system, which also produces significant environmental impacts, especially for the marine ecotoxicity category (20 % overall). Regarding climate change category, the electrical system generates 0.47 g of CO_2eq for every kWh generated. This can be split in impacts due to the manufacturing of 33 kV cable (0.01 CO_2eq/kWh), which connects the platform to the connector, and impacts related to the manufacturing of 132 kV cable (0.46 g CO_2eq/kWh), which connects the connector to the onshore substation. The significant difference between the two types of cables is primarily due to the size of the cables themselves. On the one hand, the weight of 1 m of the 132 kV cable is three times heavier than the 33 kV cable (89 vs 29 kg/m). On the other hand, the length of each cable is different: 150 m per platform in the case of the 33 kV cable, and 3.5 km to the entire tidal farm in the case of the 132 kV cable. In relative terms, the impact of climate change would be 0.31 and 0.10 t CO_2eq/m for the 132 and 33 kV cables, respectively.

Finally, the impacts of each kWh of electricity associated with the upstream module of the tidal energy farm, as well as the impacts of the operation and EoL activities (Table 8) are very small compared to the impact of the farm infrastructure (less than 5 %). The only exception is the impact of end-of-life management of the tidal farm components on marine ecotoxicity, which represents 20 % of the total impact recorded in this impact category. This is mainly caused by the recovery and recycling processes of the metallic materials that make up the structures of the platform and the mooring system, with the impact caused by the copper recovery processes being particularly relevant.

4.2. Economic results

The economic assessment was conducted in an excel spreadsheet in which all input data was integrated to model the annual cash flows during the operational life of the tidal array, which is 25 years. The tidal array comprises 23 tidal devices of 1.5 MW nominal power, for a total installed capacity of 34.5 MW. The calculation of the LCOE is based on EQ. (5), in which a discount rate of 5 % has been applied. In addition, in order to consider potential economies of scales of the tidal array, learning curve factors of 0.93 and 0.95 have been applied to CAPEX and OPEX elements (Table 4). These factors produced cost savings of 21 % and 15 %, respectively. This means that, for example, by commissioning the manufacturing of 23 platforms, the platform unit price will be 21 % lower than commissioning a single platform (the reader can refer to the supplementary material for further detail on learning curves).

The estimated LCOE is 0.125 EUR/kWh. Fig. 8 presents the percentage cost contribution to LCOE according to the main components of the tidal system. To provide this granular overview, EQ. (5) was applied iteratively for each cost element of the model. This also permitted to compare consistently the relevance of CAPEX, which generally occurs during the initial years of the tidal array and the OPEX, which instead occur yearly and remain, to a large extent, constant. Preventive maintenance costs account for approximately 26 % of the LCOE and represent the greatest economic burden over the life of the tidal array. Next, by order of magnitude, most important cost factors of LCOE concern the CAPEX. Namely the structural components of the turbine, which include the power take-off, the rotor and the auxiliary system (20 %) and the structure of the platform (19 %).

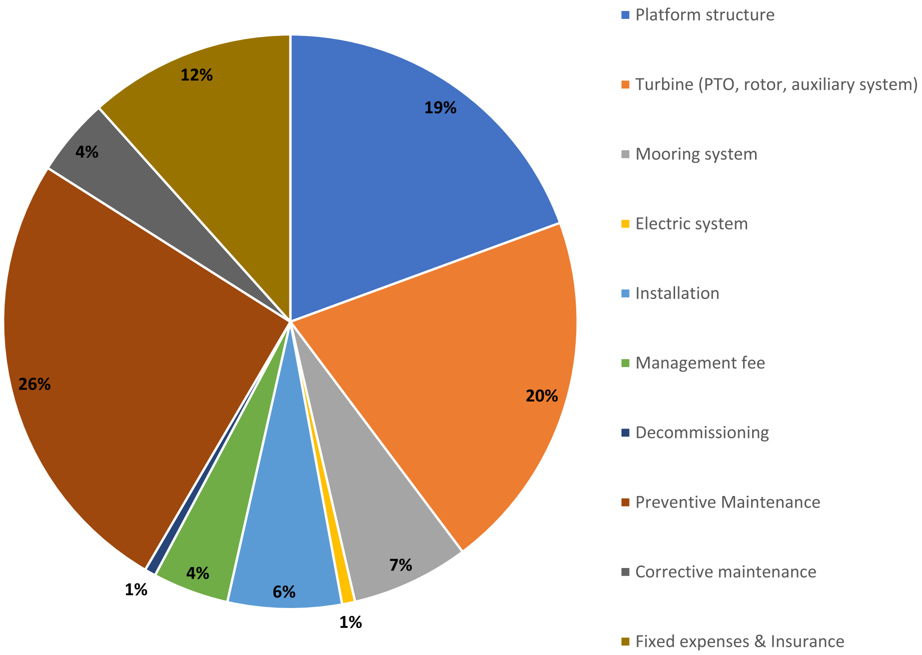

Fig. 8. Cost contribution to LCOE.

Table 9
Summary of CAPEX, OPEX in percentage (%) terms.

CAPEX Component	% contribution to CAPEX	OPEX component (annual cost)	% contribution to OPEX
Platform C_{111}	33.2 %	Preventive maintenance C_{31}	56.9 %
PTO C_{112}	9.3 %	Corrective maintenance C_{32}	11.8 %
Rotor C_{113}	24.5 %	Fixed exp. & Insurance C_{33}	31.3 %
Auxiliary system C_{114}	1.0 %		
Mooring system C_{12}	11.3 %		
Electric system C_{13}	1.3 %		
Installation C_2	11.0 %		
Management fees[a]	7.3 %		
Decommissioning C_4	1.1 %		
CAPEX TOTAL	**100 %**	**OPEX TOTAL**	**100 %**

[a] Note that the management fees have been calculated as a lump sum equal to 8 % of the CAPEX.

Table 9 summarises the share in percentage terms of the tidal components for CAPEX and OPEX cost categories. The most expensive CAPEX element is the platform, which accounts for more than 33 % of the total CAPEX. It follows the rotor, which includes the blades (24.5 %), and the mooring system (11.3 %). In line with other tidal energy projects, see e.g. Refs. [2,9,31], the manufacturing cost of all elements constituting a tidal array is the most important driver of project costs and, in this case, it covers 80.6 % of total CAPEX (remaining 19.4 % concerns installation (11 %), management fees (7.3 %) and decommissioning (1.1 %)).

On the other hand, the cost of preventive maintenance is the highest OPEX component, and it represents the 57 % of total OPEX. It is followed by insurance and fixed expenses (31 %) and corrective maintenance (12 %). Among the preventive activities, the maintenance of the bilge system, which concerns the control of the nacelle pumps, the buoys and the tightening, represents the highest cost and also causes one of the longest downtimes as it has to be carried out every three months. It follows the maintenance of the hydraulic brake system, which is also performed every three months. It should also be noted that a “full maintenance” of the platform structure to be carried out every 10 years was included. Besides being very costly, this type of activity also engenders very long downtimes (up to a month) as the platform has to be towed back to the port base. For a granular overview of preventive and corrective maintenance activities, including respective downtime, the reader can refer to the Supplementary Material Table S4 and Table S5.

Table 10

Review of LCA studies evaluating tidal energy device.

Device Name (Developer)	Location	Scope	Power rating	Lifetime (Year)	g CO_2 eq/kWh	Impact assessment	Source
Horizontal axis turbine; (Hypothetical scenario based on average figures)	na				23.1		[34]
Minesto Deep Green 500	Wales	Cradle-to-grave	0.5	25	26.3	Recipe 2010	[13]
Seagen Turbine (Marine Current Turbines Ltd.)	Northern Ireland	Cradle-to-grave	1.2	20	15	Other	[38]
SeaGen Turbine (Marine Current Turbines Ltd.)	Northern Ireland	Cradle-to-grave	1.2	25	25.5	ReCiPe 2008	[23]
HydraTidal	Norway	Cradle-to-grave	1.5	25	20.1	ReCiPe 2008	[23]
HS100	Scotland	Cradle-to-grave			37	ReCiPe 2008	[23]
DeepGen Tidal Generation Ltd. (TGL). It is a tri-blade single turbine device.	UK	Cradle-to-grave		25	34.2	Other	[33]
Open Hydro. This device is an open centre horizontal axis multi-blade turbine with a ducted housing.	UK	Cradle-to-grave		20	19.6	Other	[33]
ScotRenewables. It is a floating twin horizontal axis turbine device (SR200)	UK	Cradle-to-grave		20	23.8	Other	[33]
Flumill. This device is an original twin Archimedes' screw design.	UK	Cradle-to-grave		20	18.5	Other	[33]
Crest Energy (theoretical scheme)	New Zealand			100	1.8	Other	[39]

5. Discussion

Table 10 summarises the LCA studies conducted for Tidal Energy Converters (TECs). In general, the life cycle Global Warming Potential (GWP) is the key metric addressed by these studies [11,12,22,32], with values ranging from 15 (Seagen turbine in the north of Scotland) to 37 (HS1000 in Scotland) g CO2 eq/kWh, depending on the type of tidal energy technology considered. Similar findings were observed in the study by Walker et al. [33]. They compared LCA results for four different TECs tested at the EMEC[3] site and found the GWP ranging between 18 and 35 g CO2 eq/kWh for these devices. Only few LCAs have explored a broader set of impact categories [22,23,34,35], accounting for additional ecosystem impacts such as eutrophication and ecotoxicity.

As shown in Table 10, empirical findings can vary significantly based on the technical specifications and parametric assumptions of individual case studies. Nevertheless, scholars unanimously acknowledge that, from a LCA standpoint, the primary environmental impacts of tidal energy derive from the use of materials, particularly steel and copper, during the manufacturing phase. End-of-life disposal of the devices can also pose environmental challenges. In contrast, activities like installation, maintenance, and operation generally have negligible effects across all device types analysed [12,34]. This distinction is fundamental compared to energy systems relying on fossil-based raw materials, where most environmental impacts occur during the operational phase of the plant [36,37].

The GHG emissions obtained in this study, 42.11 g CO_2 eq/kWh, are generally higher than the emissions found in the literature. Besides LCA modelling assumptions,[4] one of the reasons that could explain this difference is related to the impact generated by the floating platform manufacturing, since this platform is the largest and heaviest component (360 tonnes) of this tidal device. Another key reasons can also relate to the different ways of EoL modelling. As an example [23], model the EoL representing only virgin material as an input and giving credits (negative flows) as an output based on recycling rates. This is different to the way the EoL has been modelled in this study, in which a content of around 20 % of secondary raw material (iron scrap) is considered as an input in the dataset used to simulate low-allowed steel, which is the main material used to simulate the impact of the platform structure; and no credit however has been applied to the recycling at the EoL.

Regarding the economic assessment, Table 11 outlines the key findings obtained from the literature review on economic studies and reports related to tidal current energy technologies. The Energy Innovation Needs Assessment report [40] estimates the current LCOE of tidal stream energy at 0.30 GBP/kWh, anticipating a potential reduction to 0.15 GBP/kWh with a 100 MW deployment, mainly attributable to decreased Operating and Maintenance cost (O&M). Comparable figures are reported by the International Renewable Energy Agency (IRENA) [1], indicating a current LCOE ranging from 0.20 to 0.45 USD/kWh, with a projected decrease to 0.11 USD/kWh by the early 2030s. Conversely, in 2015, the EC proposed LCOE targets for tidal energy, which have become widely recognised benchmarks. These targets include achieving 0.165 USD/kWh (0.15 EUR/kWh) by 2025 and further reducing it to 0.11 USD/kWh (0.10 EUR/kWh) by 2030 [5].

Despite the objectives and forecasts reported in the various sectoral report and policy strategies, only a limited number of studies

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[3] European Marine Energy Centre.

[4] Comparability of LCA results is particularly critical when different systems are being assessed as functional unit, scope and system boundary, among others, often differ. In addition, the use of different databases (or different versions of these), impact assessment methods and energy mixes can also produce different results.

Table 11
Review of economic assessment studies evaluating tidal energy devices.

Tidal Energy Converter (TEC) description	Location	Nominal capacity (MW)	Life-time	Discount rate	LCOE	CAPEX M EUR/ MW	OPEX Yearly M EUR/MW	Source
IRENA current costs tidal energy (2020)	Europe	–	–	–	0.20 USD/kWh **(0.21 EUR/kWh)** – 0.45 USD/kWh **(0.47 EUR/kWh)**	–	–	[1]
EC targets for tidal LCOE (2015)	Europe	–	–	–	0.10 EUR/kWh **(0.13 EUR/kWh)** -0.15 EUR/kWh **(0.19 EUR/kWh)**	–	–	[5,8]
Tidal test site for a second-generation horizontal tidal turbine - 6 TECs of 2 MW (2020)	Minho estuary (PT)	12	20	15 %	na	0.37 **(0.44)**	0.40 **(0.48)**	[2][a]
GEMSEY second-generation (floating) horizontal tidal turbines - 42 TECs of 1.2 MW (2020)	Alderney Race (UK)	50	20	na	0.165 EUR/kWh - **(0.197 EUR/kWh)**	1.96 **(2.34)**	0.20 **(0.24)**	[29]
Tidal farm of first-generation (fixed to the seabed) - 42 TECs of 1.2 MW (2017)	Alderney Race (UK)	50.4	20	3 %	0.150 EUR/kWh - **(0.187 EUR/kWh)**	2.76 **(3.43)**	0.10 **(0.12)**	[9]
Second-generation tidal farm inspired by the Aquantis C-Plane device (2014)	Gulf Stream off the southeast coast of Florida (USA)	40	20	na	0.247 USD/kWh **(0.236 EUR/kWh)**	0.87 M USD/MW **(0.83)**	0.17 M USD/MW **(0.16)**	[18][a]
First-generation tidal farm inspired by the SeaGen system (2014)	Tacoma Narrows tidal site (USA)	11	20	na	0.41 USD/kWh - **(0.392 EUR/kWh)**	na	na	[18][a]

[a] The study is a demo testing, most of the values are extrapolated from the literature and may not reflect, to a large extent, the real cost of the TEC technology. In bold, inflation-adjusted values are provided, referenced to the year 2023, and converted into EUR currency.

explicitly delve into the economic feasibility of these systems and the methodologies used to estimate them. Among the most recent empirical studies, Segura et al. [9] assessed the LCOE of a 50.4 MW tidal energy array – first-generation device – and found it to be approximately 0.15 EUR/kWh. In a separate study, López et al. [29] estimated the LCOE of 0.165 EUR/kWh and 0.204 EUR/kWh for a second generation 50 MW array project. These estimates were derived considering tidal devices with controllable and fixed pitch system. Higher LCOE figures were provided in Neary et al. [18], who modelled theoretical tidal arrays based on first and second-generation TECs. Similarly, Diaz et al. [2] conducted an economic assessment of a tidal test site for a second-generation horizontal tidal turbine. However, the findings from these latter studies [2,18], were primarily of a conceptual nature and based on literature data. Regarding the CAPEX, it was observed to vary between 2.76 [9] and 0.37 [2] M EUR/MW. This notable difference is attributed to the technological leap from first-generation devices (anchored to the seabed) to second-generation devices (floating, connected to the seabed via mooring lines or anchoring lines).

5.1. Sensitivity analysis

The lack of a standardised economic assessment approach limits a consistent comparison among studies, especially regarding the LCOE, since it is highly sensitive to factors such as annual energy production, TEC lifetime, discount rate applied, and the rate of economies of scale. Therefore, in this section, we present a sensitivity analysis in which we explore how the LCOE might vary as the parameters that most influence its behaviour change. These parameters are.

1) the tidal free stream velocity, which directly affects the AEP
2) the operational availability, which also directly affects the AEP.[5]
3) the platform structure, which was identified as the most expensive CAPEX element
4) the preventive maintenance, which was identified as the most expensive OPEX element

The parameters were tested by means of local sensitivity analysis (SA). Local SA describes a variation of one input variable around a base value keeping all other input variables fixed. The resulting change of the model output in relation to the input variation is

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[5] It should be noted that, theoretically, operational availability is related to O&M cost: a lower operational availability is generally due to more – or longer– maintenance/repairing activities, which represent more expensive O&M. However, in this analysis we treated 0&M and operational availability as independent factors.

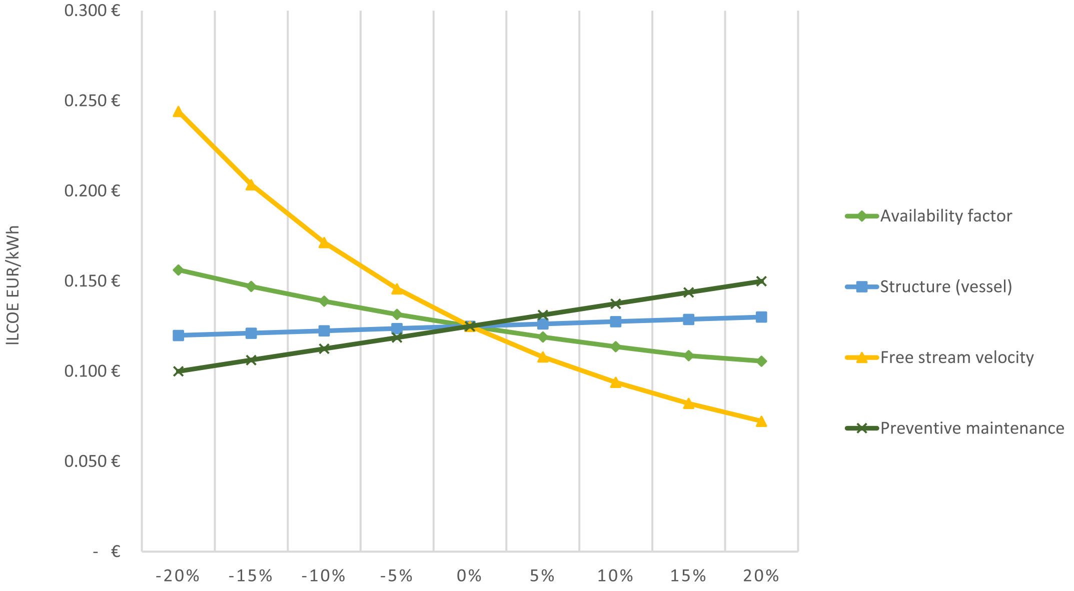

Fig. 9. Sensitivity analysis of LCOE drivers.

quantified as the sensitivity measure. In this case, the variation has been set from −20 % to +20 %. Calculated results are provided graphically as a spider chart (the steeper the slope, the stronger the sensitivity) in Fig. 9.

The most important parameter is the tidal free stream velocity. In particular, when the tidal speed is reduced by 20 % the LCOE increases up to 0.244 EUR/kWh, which is almost the double. This is a key aspect that shows how the same technology may have a significantly different performances due to totally external factors.[6] The following key parameter influencing the most the variation in the LCOE is the operational availability. A further reduction of operational availability by 20 % would increase LCOE up to 0.156 EUR/kWh. By contrary, operational improvement by the same order of magnitude would produce a LCOE equal to 0.106 EUR/kWh. Similar results are obtained from varying the cost of preventive maintenance. In this case, the LCOE might range between 0.150 EUR/kWh (+20 % preventive maintenance) and 0.100 EUR/kWh (−20 % preventive maintenance). Interestingly, the variation in the cost of the platform produces a relatively lower impact on the LCOE. Indeed, a ±20 % variation would still generate a LCOE aligned with the EC targets.

The economic results of this study show that current LCOE for tidal energy may be lower than IRENA estimates. Notably, the expected LCOE of the tidal array based on the Atir tidal device is 0.125 EUR/kWh, which is below the 0.15 EUR/kWh target set by 2025. It should also be noted that the EC expected targets have been estimated considering learning rates higher than those considered in this study (i.e., learning rate 12 % vs 7 % and cost reductions from 45 % to 75 % vs 21 %–23 %). Hence, the LCOE could be even lower by applying the optimistic learning rates of the IRENA study.

Regarding CAPEX and OPEX indicators, the results show that the Atir device incurs in higher upfront expenses due to the significant cost of the platform structure, which represents up to 34 % of the CAPEX. However, this is amortized over the life cycle of the tidal plant thanks to a relatively low OPEX. In fact, the Atir does not require any construction on the seabed, thereby avoiding complex maintenance work. Furthermore, it facilitates the execution of a majority of maintenance activities directly from inside the platform, effectively lowering both the overall maintenance costs and operational downtime.

While this analysis can offer valuable insights into the environmental and economic impacts of tidal technology, it is crucial to acknowledge its inherent limitations. These limitations stem from the broad spectrum of assumptions and parameters involved, which in turn make achieving consistent comparisons challenging. As an example, decisions such as discount rate selection can generate very different results regardless of the intrinsic cost of the tidal device. Likewise, operational life of tidal parks or learning rates are also key parameters that can significantly change LCOE results. Therefore, the comparison of existing tidal technologies should always be done with caution. In addition, notwithstanding the technical efficiency of tidal technology, the economic and environmental outcomes of a tidal project strongly are significantly contingent upon the tidal site characteristics. Key factors include the site's tidal current speed and the arrangement of the array, both of which heavily influence AEP. The flows in straits and channels where tidal devices are installed will vary not only due to interactions with devices but also because of complex bathymetry, alignment, and turbulence issues. Hence, the omission of these constraints likely overestimated the LCOE. This limitation needs to be thoroughly addressed in future studies. As demonstrated by the sensitivity analysis, variations in tidal speed can yield vastly different LCOE results for the same tidal

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[6] To note that this analysis was motivated during the project to compare the economic performance between the deployment of the tidal system in the Fall of Warness area (Scotland), which is the scenario presented in this article, and the Morlais area (Wales). This latter is characterized by significantly lower tidal speeds.

device. This correlation extends to the environmental impacts per kWh of electricity generated. Policymakers should consider these site-specific factors when formulating strategies and policies for the deployment and support of tidal energy projects, recognizing the pivotal role played by tidal site characteristics in project viability and sustainability.

6. Conclusions

The aim of this work has been to perform a joint environmental and economic assessment of a 34.5 MW tidal energy array based on the Atir pilot, a second-generation tidal device operating since 2018 in Orkney, Scotland. The economic analysis shows that the LCOE of the Atir device, estimated at 0.125 EUR/kWh, is in line with European Commission projections. The Atir requires very high CAPEX costs due to the platform structure. In the long run, however, these costs can be offset by the benefits obtained in OPEX terms.

On the other hand, LCA results show that the system under study emits 42.11 g CO2eq per kWh of electricity produced. These emissions mainly come from the manufacturing process of the platform and mooring system, as both elements require large amounts of steel. In general, the production of steel structures is the main impact factor across all environmental categories of the ReCiPe MidPoint method, except for the freshwater and marine ecotoxicity indicators. In the latter cases, in addition to the production processes, end-of-life activities also take on great importance since they deal with copper-based electronic components.

The findings from the Atir device underscore the importance of optimising the design of tidal devices to minimise the environmental impacts associated with components production and to generate electricity with a low environmental footprint. In this line, potential strategies may include.

- prolonging the useful life of the equipment
- implementing total or partial equipment reuse
- reducing the weight of equipment through eco-design
- enhancing electricity production efficiency either by seeking locations with high potential for tidal power generation or by improving equipment efficiency.

This study also presents a framework for conducting LCA and economic assessment. In this context, the joint evaluation of environmental and economic indicators is key for informed decision-making. In this case, the relatively high cost of the platform structure, coupled with the substantial environmental impact linked to its construction, prompted Magallanes to explore “circular-oriented” options within its R&D activities. These options include the remanufacturing and retrofitting of existing ships, as well as an increased focus on the reuse of equipment such as generators.

To conclude, future work in the LCA and LCC of TECs can focus on several key areas. First, one challenge in conducting LCA of TECs is the industry’s lack of data and transparency. Therefore, further efforts can be made to collect more data and share them among stakeholders, including manufacturers, researchers, and policymakers. Expanding the life cycle inventory to cover the entire TEC supply chain is necessary, incorporating primary data for upstream processes. Likewise, consideration of data on the spatial variability of tidal flows is critical to refine energy production modelling and produce more robust LCOE estimates. Second, while a conventional LCC approach was adopted in this study, there is recognition that monetising environmental impacts would offer a more comprehensive evaluation of overall expenses linked to renewable energy projects [41,42]. This inclusion would ensure a thorough understanding of the true economic impact, encompassing environmental considerations. Finally, beyond LCA and LCC analyses, examining the socioeconomic impacts on local communities is crucial for policymakers seeking community acceptance [43,44]. Hence, future work is suggested to integrate socioeconomic impacts, including job creation and gross value-added generation.

Data availability statement

Data associated with this study has been not deposited into a publicly available repository. Non confidential data is included in article/supp. material/referenced in article.

CRediT authorship contribution statement

M. Bianchi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A.J. Arnal:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. **M. Astorkiza-Andres:** Investigation. **J. Clavell-Diaz:** Investigation. **A. Marques:** Validation, Data curation. **M. Isasa-Sarralde:** Project administration, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Marco Bianchi reports financial support was provided by European Commission. A. Marques reports a relationship with Magallanes Renovables that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research has been supported by the EU Horizon 2020 research and innovation programme under grant agreement Nº 815278. The authors gratefully acknowledge Mr. Mario Iglesias, manager of Magallanes Renovables, for providing the data necessary to carry out the analyses of this research. The authors are also grateful to four anonymous referees for their constructive comments and suggestions. Any remaining errors are solely the authors' responsibility.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e32515.

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