Journal of Ocean Engineering and Marine Energy
https://doi.org/10.1007/s40722-026-00487-0

CASE STUDY

Life cycle assessment of wave energy: the Mutriku case study

Rosario León Lira[1] · **Leonor Patricia Güereca**[1] · **Jon Lekube**[2]

Received: 18 August 2025 / Accepted: 27 February 2026

Abstract

Environmental impacts and the effects of climate change are becoming ever higher as the energy demand is growing, and the high dependence on fossil fuels to supply global energy needs is unquestionable. For this reason, it is necessary to increase the global percentage of renewable energy (ODS 7, target 7.2), promote access to research, technology and investments in clean energy (ODS 7, target 7.4) and integrate climate change measures into national policies, strategies and planning (ODS 13, target 13.2). In this sense, ocean energy has a relevant role, but it is necessary to identify the environmental effects it may generate. According to the later, the aim of this research is to evaluate the environmental impacts of a wave energy power plant located in Mutriku, Spain, with a Life Cycle Assessment approach. The results demonstrate that the Construction stage presents the highest environmental impacts, which reach 86.6% in climate change due to the high raw materials consumed, while energy generation is the stage with the lower environmental impacts, with 5.5% in the climate change category. For the end-of-life stage a sensitivity analysis was performed, showing that high recycling rates for all the metallic materials is not always resulting in better performance. It is concluded that it is important to mitigate the environmental impacts in the Construction stage and in the End-of-Life stage.

Keywords LCA · Environmental impacts · Ocean energy · Oscillating water column · Wave energy converter · Spain

1 Introduction

Within the 17 Sustainable Development Goals (SDG), two of them call for action towards energy sustainability: the SDG 7: Affordable and Clean Energy—ensure access to affordable, reliable, sustainable, aims to increase the global percentage of renewable energy (target 7.2) and promoting access to research, technology and investments in clean energy (target 7.4), among other targets. On the other hand, the SDG 13: Climate Action—take urgent action to combat climate change and its impacts, integrating climate change measures into national policies, strategies and planning (target 13.2) and improving education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning (target 13.3). However, despite the efforts of the international community to achieve the SDGs and reduce the consumption of fossil fuels and the Greenhouse Gases (GHG) emissions, in 2022 80% of energy was provided by fossil fuels (IEA 2023a), generating 36,900 million tons of CO_2 eq (IEA 2023b), which represents 68% of the total GHG emissions (Crippa et al. 2023).

To avoid the GHG emissions, the International Energy Agency (IEA) has highlighted the need to increase the development of clean energy generation technologies and infrastructure (IEA 2023a). In this sense, renewable energies are considered an effective and promising solution for the energy supply with low carbon emissions (Panwar et al. 2011).

Within renewable energies, it is estimated that ocean energy represents a total potential up to 80,000 TWh per year (approximately 10% of the world's current electricity demand), with an additional benefit of being more predictable than other renewable sources, which is an important characteristic for meeting the goal of generating low-carbon energy (Guercio and Kumar 2022). However, according to the International Renewable Energy Agency (IRENA), by 2024 there was only an installed capacity of 494 MW worldwide, which

✉ Leonor Patricia Güereca
LGuerecaH@iingen.unam.mx

[1] Engineering Institute, Universidad Nacional Autónoma de México, Av. Universidad 3000, C.P. 04510 Mexico City, Mexico

[2] Renewable Energy and Resource Usage Area, Basque Energy Agency (EEE/EVE), Urkixo Zumarkalea, 36, 48011 Bilbao, Spain

includes all forms of energy extraction from the ocean. This capacity is mainly concentrated in Europe, where France has the only tidal power plant with a capacity of 212 MW, followed by the United Kingdom with a capacity of 10 MW and Spain with an installed capacity of 5 MW, and in Asia, where South Korea has a capacity of 255 MW. This contrasts with the installed capacity of wind energy, which reaches 1,132,657 MW worldwide and solar energy, which represents 1,866,306 MW worldwide (IRENA 2025).

Among the energies of the ocean, wave energy consists of using the movement of the waves, harnessing both in its kinetic and potential form for its transformation into electrical energy (Paredes et al. 2019). These devices are usually known as Wave Energy Converters (WEC) and consist of at least three elements: (1) the extraction method, (2) the power generation system or power take-off, and (3) the support structure (Paredes et al. 2019; Uihlein 2016). They can be classified according to the location they are installed in, namely onshore, nearshore or offshore, or the operating principle they are based on to convert wave energy into electricity (Gastelum 2017).

Amid the different types of WECs, the Oscillating Water Column (OWC) is a device with a partially submerged cavity structure where the air, acting as a working fluid, moves an air turbine alternating compression and decompression in response to the incident waves (Cascajo et al. 2019).

Currently, the vast majority of ocean energy systems installed are testing prototypes whose only objective is to prove the feasibility of the concept in terms of power capture and conversion, robustness and affordability. These prototypes are usually built and tested for a period comprised between six months and a couple of years in the best-case scenario, producing a considerable amount of waste and junk at the end of each testing campaign. The actual lifespan that these devices will have at the commercial stage is still unknown, even though some estimations put the lifespan of WECs between 20 and 30 years, leaving this issue to be addressed in the medium-term future. Bearing this in mind, the EU's Offshore Renewable Energy Strategy, launched by the European Commission in 2020 (European Commission 2020), established for the first time, increase production efficiency, longer life-time of installations and the 'end of life' of components, considering the circular economy approach by including the principle of 'circularity by design' through the research and innovation (European Commission 2020), which is expected to trigger advances in the development of ocean energies.

Although the use of wave energy seems to be an attractive alternative to fossil fuels electricity production, it is important to note that there are many factors that limit the use of WECs, namely degree of development, efficiency, high investment costs or social acceptance (Panwar et al. 2011; Tello and Marulanda 2017; Lund 2007; Bhat and Prakash 2009; Wilberforce et al. 2019). In this regard, an example of success in increasing the supply of renewable sources in its energy matrix is the autonomous community of the Basque Country in northern Spain, where in 2000 these represented 3.3%, while by 2024 this had increased to 7.9%, with 0.1% of this energy coming from a wave energy system since 2011 (EVE 2026).

Additionally, the environmental impacts are of keen interest due to the potential damage on wildlife and the surrounding environment, as well as the environmental impacts associated directly and indirectly to the resource use and energy (Sørense et al. 2006; Mustapa et al. 2017; Ozkan 2020). Emissions, effluents and solid waste produced during the fabrication, installation, operation and decommissioning of these devices have a direct impact on the depletion of natural resources, climate change and depletion of fossil fuels, among other impacts (Paredes et al. 2019; Patrizi et al. 2019; Pennock et al. 2021).

In order to assess the environmental impacts of the electricity production based on ocean energies, in this paper, a Life Cycle Assessment (LCA) of an OWC-type WEC is developed, using as a case study the Mutriku Wave Energy Power Plant in Spain. This plant was selected for being one of the few wave power plants currently in operation worldwide, and the first of its class to be connected to the local power grid supplying, therefore, continuous electricity on a commercial scale (Fernández 2017; Lekube et al. 2018; Vicinanza et al. 2019; Torre-Enciso et al. 2009; Garrido et al. 2015; Ibarra et al. 2018; Serras et al. 2019; Faÿ et al. 2020). Another of the main advantages of this plant is that it is a research center, which provides the possibility of testing prototypes in real conditions, which accelerates the project development process in marine energy (Fernández 2017; Faÿ et al. 2020).

Among the main challenges of WECs is that only a small number of them have reached sea trials and a few prototypes have been tested in real environmental conditions (Faÿ et al. 2020). Therefore, LCA is a useful tool throughout the development stages of a WEC, since for those in the design stages it allows identifying critical points and taking actions (Apolonia and Simas 2021), while for installations, like Mutriku, already functional, allows the components and operations of these devices to be exhaustively represented so that the assumptions for these technologies can be validated and the knowledge gaps that exist in them can be closed (Pennock et al. 2021).

In this sense, Life Cycle Assessment methodology has proven to be a tool that helps identify the potential environmental impacts at every stage of an ocean energy system. Therefore, it is considered an important tool for understanding the potential impacts of devices that generate energy through the ocean, so that decision makers have a method of evaluating environmental performance and better understand whether these technologies are not only technically and economically viable but also environmentally feasible (Guercio and Kumar 2022; Paredes et al. 2019; Güereca et al. 2015; Bastos et al. 2023), and really contribute to achieving an affordable and clean energy (SDG 7) and to combat climate change and its impacts (SDG 13).

Most of the studies reported in the literature focus on the carbon footprint (Gastelum 2017; Patrizi et al. 2019; Parker et al. 2007; Walker and Howell 2011; Banerjee et al. 2013) with little information about the various environmental impacts that these systems can generate (Paredes et al. 2019). In addition, most studies are on technologies at early readiness levels, so a detailed understanding of the life cycle impacts of WECs is important for their technological development, maturation and commercialization (Zhai et al. 2018), even to achieve a decrease in their Energy Payback Time.

2 Material and methods

2.1 Scope definition

The harbor of Mutriku is located in a small bay in the Gulf of Biscay on the northern coast of Spain. In the Breakwater of Mutriku, the Basque Energy Agency of Basque Country (EVE for its acronym in Spanish, *Ente Vasco de la Energía*), installed the power plant.

The function of this power plant is the commercial production of electricity and the supply of energy to a portion of the Mutriku community. The Functional Unit (FU) established was 1 kWh, in order to compare with other LCA studies with similar devices. The lifespan has been considered as 20 years, the lifetime for which the power plant was designed.

The energy production considered for this study was 4,929,377 kWh during the estimated lifetime, considering the annual average energy production, based on Fernández (2017), Ibarra et al. (2018) and Serras et al. (2019), estimations.

2.2 Life cycle systems boundaries

The approach used for this LCA was "cradle to grave," meaning that all necessary processes were considered, from the acquisition of raw materials to the final disposal of the resources used, through the established life cycle stages (ISO 2006). For ocean energy systems, these stages can be defined as Construction, generation, and end of life, according to Paredes et al. (2019), as shown in Fig. 1 and described in Sect. 2.2.

2.3 System description

2.3.1 Construction stage

In this stage, all the materials for the Breakwater structure as well as all those required for the wave power plant are included. The Breakwater has a half-moon shape with 600 m large where 100 m consists of the active zone, where the wave power plant, with its sixteen air chambers, is located (Supplementary material—Fig. S1).

The wave power plant consists of prefabricated concrete trapezoidal blocks that are built on top of each other and are filled with concrete (type HA-35/P/20/IIIc+Qb with cement CEM III/B 32,5R), of structural steel, designed to have high strength and durability in a marine environment. It is integrated with sixteen air chambers, all with the same dimensions, which are connected through an overhead opening into a turbine gallery where Wells-type turbines are installed, each connected to a generator with a rated power of 18.5 kW. The lower level of the opening, wherewave energy extraction is carried out, is 3.4 m below the Lowest Equinoctial Spring Tide (Lekube et al. 2018; Torre-Enciso et al. 2009, 2010; Garrido et al. 2015; Faÿ et al. 2020; Tease et al. 2007; Arcelay 2020; Otaola et al. 2019) (Supplementary Information—Fig. S2).

Wells turbines installed in Mutriku have a height of 2.83 m and 1.25 m wide. In addition, each turbogenerator module includes two five-bladed rotors (Torre-Enciso et al. 2009, 2010; Ibarra et al. 2018). Each rotor is formed by symmetrical blades that rotate in the same direction regardless of the direction of the air flow through the turbine, so no additional device is required to rectify this flow (Torre-Enciso et al. 2009; Otaola et al. 2019).

On the other hand, the equipment of the power plant is divided into two groups, each with 8 turbines, for control purposes (Tease et al. 2007). The generator has a voltage of 460 V, which is considered low voltage. To fulfill the requirements of the power grid, the power is generated in alternating current, then rectified to direct current and back again into alternating current through a back-to-back converter. The Mutriku wave power plant is capable of supplying its own electrical needs, with the remaining energy being supplied to the local distribution grid at 13.2 kV (Lekube et al. 2018; Torre-Enciso et al. 2009; Ibarra et al. 2018).

At this stage, cabling and raw material transport were not considered. This is because Uihlein (2016) demonstrated that the cabling contributes less than 10% to the climate change impact category, while Patrizi et al. (2019), identified that transport only represents 1% of the impacts in a study of

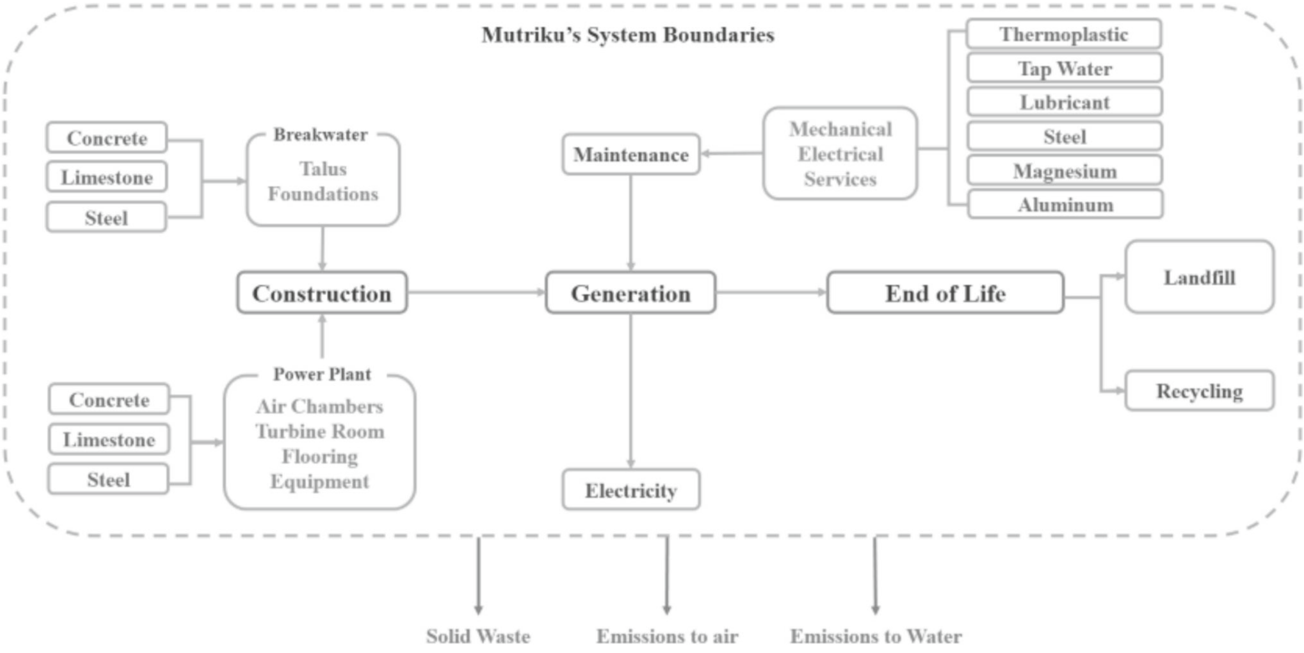

Fig. 1 Mutriku's wave energy power plant system boundaries

an OBREC device installed in a Breakwater similar to the Mutriku plant. It is important to note that Mutriku plant is located at 13 and 25 km of two cement production plants, and at 25 and 32 km of two steel production plants, so it is assumed that the impacts of transporting materials are not significant.

During the operation, since no inputs or other raw materials are required other than the movement of the waves to move the turbines and generate energy, there is no production of waste, emissions or effluents in this sub-stage. The maintenance of the dam is responsibility of the port authority, so it is not considered as part of the systems.

2.3.2 Generation stage

In this stage, the electricity generation and maintenance are included (Fig. 1). The maintenance of the wave power plant is performed annually both for preventive and corrective purposes; monthly reviews are performed and depending on the degree of wear of each component, is that it is intervened. During these activities, both mechanical and electrical components are replaced (Lekube et al. 2018). This includes maintenance of the electrical and mechanical systems, the water needed for the sanitary services of the plant, and the cleaning of the Wells turbine blades (Lekube et al. 2018). Maintenance of the electrical system consists of quarterly checks of the electronic devices, while the mechanical system requires greasing of the bearings, replacement of the bearings as well as replacement of the turbine rotors.

As a result of the spatial configuration of the Breakwater of Mutriku Wave Energy Power Plant, as well as plant maintenance activities, the number of active turbines is not always the same, but it is estimated that, on average, 10 turbines are in constant operation and this value is used in the Life Cycle Inventory.

2.3.3 End of Life (EoL)

Mutriku power plant has not yet concluded the lifespan for which it was designed, so for this stage, for the reference scenario (E1), the recycling rate was assumed for the metal elements that compose the wave power plant to be 90%, which is the one typically assumed for renewable energy generation technologies (Karan et al. 2019) and the one proposed for other WEC's (Parker et al. 2007; Zhai et al. 2018; Dalton et al. 2014; Douziech et al. 2016; Thomson et al. 2019), while the rest of the metals (10%) and the other materials (concrete, limestone) used in the different stages of the lifecycle of the power plant are assumed to be deposited in a landfill. For the non-metallic materials, it is considered that 100% are disposed in sanitary landfills. Due to a lack of data, the dismantling process is considered not to generate emissions or discharges.

Transportation was excluded from this stage of the life cycle for the following two reasons: first, the average distance between the various waste segregation transfer centers in the Basque Country and the port of Mutriku, where the Wave Energy Plant is located, is 19 km; second, other authors have suggested that transportation is not as crucial (Uihlein 2016; Bastos et al. 2023).

On the other hand, and considering that the End-of-Life (EoL), is currently the stage of highest uncertainty in ocean energy generation systems, because there are still no studies on the actual disposal or recycling practices of the different materials that make up the technologies (Zhai et al. 2018), a sensitivity analysis of the EoL scenarios is performed, considering the scenarios presented in Table 1.

The second scenario (E2) includes the dismantling of the wave power plant from its foundations, with a recycling rate of 75% for metallic materials, while the other 25%, as well as 100% of the rest of the materials used are disposed of in a landfill. Finally, the third scenario (E3) includes the dismantling of the wave power plant from its foundations, with a recycling rate of 50% for the metallic materials, while the other 50%, as well as 100% of the rest of the materials used are disposed of in a landfill. Recycling rates for all scenarios are shown in Table 1.

2.4 Life cycle inventory

The Life Cycle Inventory (LCI) for the generation stage was provided by the Mutriku staff, mainly by Dr. Lekube, author of this paper and who was Project Manager of the Basque Energy Agency, site that operates and maintains the wave power plant in Mutriku. Meanwhile, for the Construction and the EoL stages, data from secondary sources (Torre-Enciso et al. 2009; Parker et al. 2007; Zhai et al. 2018; Arcelay 2020; Dalton et al. 2014; Douziech et al. 2016; Thomson et al. 2019) and international databases (Ecoinvent v3.4; GaBi Database) were used. Table 2 shows the summary of the LCI for the Mutriku wave power plant and the ecoinvent modules used for the Life Cycle Impact Assessment (LCIA), which show the characteristics of each material.

2.5 Life cycle impact assessment

The method selected in this research for LCIA was ReCiPe v1.08 Midpoint and modeling was performed using the GaBi Thinkstep software. In this study, nine impact categories were modeled in the LCIA stage, which have been previously identified as relevant for this type of systems by Paredes et al. (2019): Climate Change (CC) in kg CO_2 eq, Fossil Depletion (FD) in kg oil eq, Human Toxicity (HT) in kg 1,4-DB eq, Marine Ecotoxicity (MET) in kg 1,4-DB eq, Marine Eutrophication (ME) in kg N eq, Metal Depletion (MD) in kg Fe eq, Ozone Depletion (OD) in kg CFC-11 eq, Particulate Matter Formation (PMF) in kg PM_{10} eq and Terrestrial Acidification (TA) in kg SO_2 eq.

2.6 Energy payback time

As part of this work, a preliminar estimation of the Energy Payback Time (EPBT) was performed. EPBT refers to the ratio of embodied energy to the annual net electricity generation in an energy production facility. The calculation includes the use of the embodied energy values of the raw material and energy used in the Construction and Generation stages, divided by the annual production of energy. The embodied energy of raw materials were adopted from Alcorn A., (2001) and divided by the annual electricity production considered in this paper.

3 Results and discussion

3.1 Life cycle impact assessment

In Table 3 is shown the results of the Life Cycle Impact Assessment profile of Mutriku Wave Energy Power Plant for each of the impact categories analyzed, as well as for the different stages and sub-stages described in Sect. 2.3 of this paper. Also, Fig. 2 shows the normalized and percentual results of the life cycle stages.

Climate change is the most frequently reported environmental impact category in the literature (Gastelum 2017; Patrizi et al. 2019; Parker et al. 2007; Walker and Howell 2011; Banerjee et al. 2013). In this study, a total impact of $2.26E{-}01$ kg CO_2 eq/kWh was estimated, of which $1.95E{-}01$ kg were generated during the Construction stage. This value represents the highest impact, comparing with other studies, which is discussed in detail, at the end of this section.

With regard to the ozone depletion impact category in Table 3, a value of $2.11E{-}08$ kg CFC-11 eq/kWh can be observed, which is higher than that reported by other authors and varies between $2.50E{-}09$ and $6.32E{-}09$ kg CFC-11 eq/kWh for an Oyster-type system (Karan et al. 2019), but lower than those reported by Uihlein (2016) for devices such as Pelamis ($1.80E{-}03$ kg CFC-11 eq/kWh) and a Point Absorber ($4.20E{-}20$ kg CFC-11 eq/kWh).

Douziech et al. (2016) report lower values for the categories: Fossil Depletion ($2.28E{-}02$ kg oil eq/kWh), Human Toxicity ($3.39E{-}02$ kg 1,4-DB eq/kWh), Marine Ecotoxicity ($1.64E{-}03$ 1,4-DB eq/kWh), Marine Eutrophication ($1.92E{-}05$ kg N eq/kWh), Particulate Matter Formation ($1.43E{-}04$ kg PM_{10} eq/kWh) and Terrestial Acidification ($2.51E{-}04$ kg SO_2 eq/kWh), compared to those presented in Table 3. On the contrary, they report a higher value in the Metal Depletion category ($5.38E{-}08$ kg Fe eq/kWh) than that obtained in this study ($3.21E{-}03$ kg Fe eq/kWh). It is important to note that none of these systems, despite being

Table 1 Scenarios considered for EoL stage and its recycling rate assumed

	Metals [%]		Non-metallic materials [%]	Other materials [%]
	Recycling	Landfill	Landfill	Landfill
E1	90	10	100	100
E2	75	25	100	100
E3	50	50	100	100

Table 2 Life cycle inventory of Mutriku and datasets used for the LCIA

Stage	Sub-stage	Material	Total quantity used (kg)	Reference	Ecoinvent 3.4 Module
Construction	Breakwater	Concrete	3.42*E*+05	Adapted from Arcelay (2020)	CH: market for concrete. Normal ecoinvent 3.4 (generic representation that in Switzerland corresponds to B30/25 (C20/25-C25/30)
		Limestone	2.13*E*+07	Adapted from Torre-Enciso et al. (2009)	CH: market for limestone. Unprocessed ecoinvent 3.4
		Steel	1.84*E*+03	Adapted from Adapted from Torre et al., (2009)	GLO: market for metal working. Average for steel product manufacturing ecoinvent 3.4
	Power Plant	Concrete	1.26*E*+07	Adapted from Torre-Enciso et al. (2009)	CH: market for concrete. Normal ecoinvent 3.4 (generic representation that in Switzerland corresponds to B30/25 (C20/25-C25/30).CH: market for concrete. Normal ecoinvent 3.4
		Limestone	7.65*E*+03	Adapted from Torre-Enciso et al. (2009)	CH: market for limestone. Unprocessed ecoinvent 3.4
		Steel	1.20*E*+03	Adapted from Torre-Enciso et al. (2009)	GLO: market for metal working. Average for steel product manufacturing ecoinvent 3.4
Generation	Maintenance	Thermoplastic	9.10*E*+03	Mutriku Wave Power Plant	DE: Thermoplastic polyurethane (TPU. TPE-U) adhesive ts
		Tap Water	5.98*E*+06	Mutriku Wave Power Plant	GLO: market group for tap water ecoinvent 3.4
		Lubricant	9.22*E*+01	Mutriku Wave Power Plant	GLO: market for lubricating oil ecoinvent 3.4
		Steel	1.51*E*+02	Mutriku Wave Power Plant	GLO: market for metal working. Average for steel product manufacturing ecoinvent 3.4
		Magnesium	1.39*E*+02	Mutriku Wave Power Plant	GLO: market for magnesium ecoinvent 3.4
		Aluminum	2.94*E*+03	Mutriku Wave Power Plant	GLO: market for metal working. Average for aluminium product manufacturing ecoinvent 3.4

Table 3 Absolute values of the life cycle impact assessment profile of Mutriku wave energy plant per functional unit (1 kWh) across different life cycle stages

Impact categories	Acronym	Total	Stage													
			Building			Generation			End of Life							
			Total	Breakwater	Power plant	Total	Maintenance	Operation	Total	Steel recycling	Aluminum recycling	Steel landfill	Aluminum landfill	Limestone landfill	Thermoplastic landfill	Concrete landfill
Climate change [kg CO_2 eq.]	CC	2.26E−01	1.95E−01	1.47E−02	1.81E−01	1.24E−02	1.24E−02	0.00E+00	1.79E−02	−5.66E−03	7.40E−12	3.65E−05	2.98E−06	1.54E−02	1.18E−03	6.88E−03
Fossil depletion [kg oil eq.]	FD	5.50E−02	2.81E−02	3.70E−03	2.44E−02	5.31E−03	5.31E−03	0.00E+00	2.16E−02	−1.31E−03	−5.14E−12	1.30E−05	1.06E−06	1.58E−02	3.56E−05	7.05E−03
Human toxicity [kg 1,4-DB eq.]	HT	3.95E−02	3.32E−02	2.28E−03	3.09E−02	1.72E−03	1.72E−03	0.00E+00	4.67E−03	−3.71E−05	1.34E−11	3.98E−06	3.25E−06	3.24E−03	1.12E−05	1.45E−03
Marine eco-toxicity [kg 1,4-DB eq.]	MET	1.38E−03	1.07E−03	7.88E−05	9.87E−04	1.76E−04	1.76E−04	0.00E+00	1.43E−04	−6.65E−07	5.28E−13	1.23E−08	1.00E−09	9.96E−05	4.37E−08	4.44E−05
Marine eutrophication [kg N eq.]	ME	4.67E−05	3.83E−05	1.09E−05	2.73E−05	2.15E−06	2.15E−06	0.00E+00	6.26E−06	−2.84E−07	−2.01E−15	3.83E−09	3.12E−10	4.32E−06	2.91E−07	1.93E−06
Metal depletion [kg Fe eq.]	MD	3.21E−03	7.94E−03	7.79E−04	7.16E−03	2.05E−04	2.05E−04	0.00E+00	−4.93E−03	−6.04E−03	8.50E−14	8.63E−07	7.03E−08	7.65E−04	2.38E−06	3.41E−04
Ozono depletion [kg CFC-11 eq.]	OD	2.11E−08	9.48E−09	1.65E−09	7.83E−09	3.88E−10	3.88E−10	0.00E+00	1.12E−08	3.17E−11	−2.43E−19	1.23E−19	1.00E−19	7.72E−09	3.38E−19	3.45E−09
Particulate matter formation [kg PM10 eq.]	PMF	6.44E−04	5.66E−04	2.80E−04	2.86E−04	1.59E−05	1.59E−05	0.00E+00	6.25E−05	−3.36E−06	3.64E−14	3.38E−08	2.75E−09	4.54E−05	1.51E−07	2.03E−05
Terrestrial acidification [kg SO2 eq.]	TA	8.53E−04	6.75E−04	1.91E−04	4.84E−04	2.97E−05	2.97E−05	0.00E+00	1.48E−04	−1.02E−05	−2.88E−13	9.48E−08	7.73E−09	1.09E−04	4.03E−07	4.87E−05

CC: Climate Change. FD: Fossil Depletion. HT: Human Toxicity. MET: Marine Ecotoxicity. ME: Marine Eutrophication. MD: Metal Depletion. OD: Ozone Depletion. PMF: Particulate Matter Formation. TA: Terrestrial Acidification

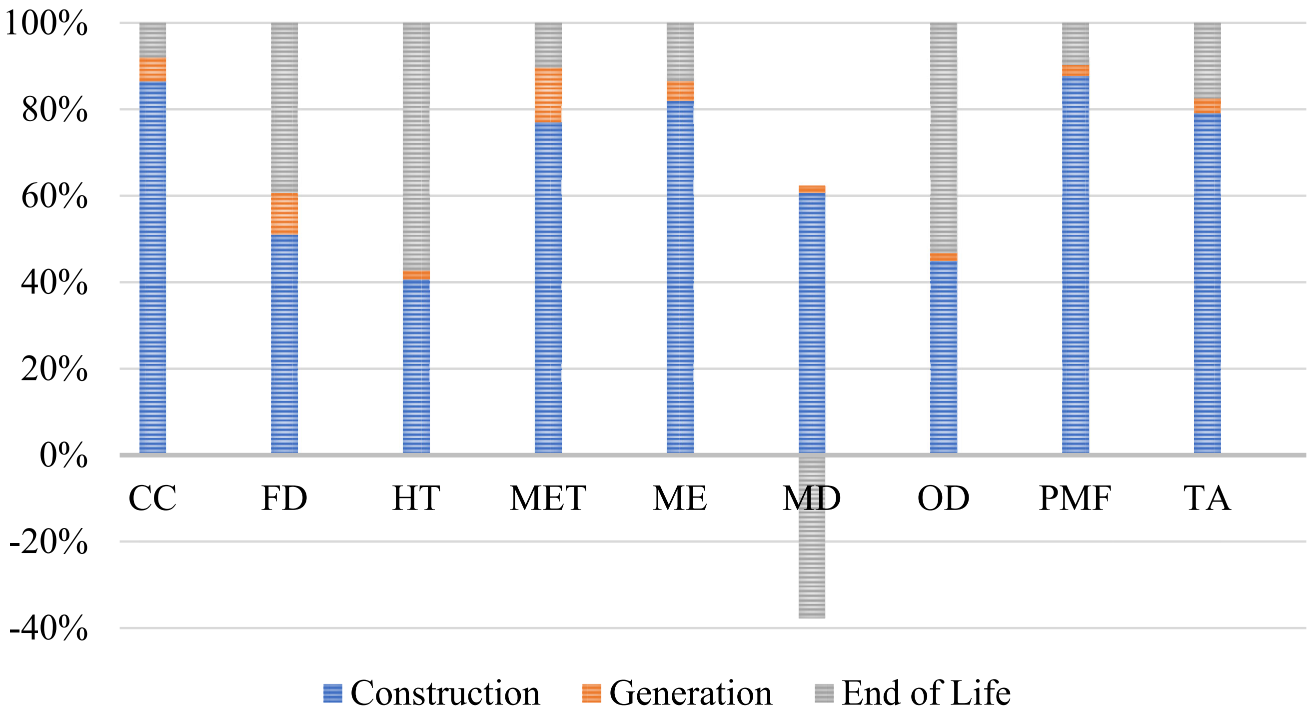

Fig. 2 Normalized and percentual life cycle impact assessment (LCIA) profile of Mutriku wave energy plant per functional unit (1 kWh) across different life cycle stages. CC: Climate Change. FD: Fossil Depletion. HT: Human Toxicity. MET: Marine Ecotoxicity. ME: Marine Eutrophication. MD: Metal Depletion. OD: Ozone Depletion. PMF: Particulate Matter Formation. TA: Terrestrial Acidification

wave energy systems, are the same, which makes comparison difficult.

As can be seen in Table 3 and Fig. 2, in all impact categories, Generation is the stage with the lowest impacts, from 2 to 12.7%, which agrees with other life cycle studies of ocean energy devices, where it is stated that generation has minimal impacts (Paredes et al. 2019; Parker et al. 2007; Zhai et al. 2018; Thomson et al. 2019, 2011; Dahlsten 2009). This is mainly due to the fact that during the operation only the movement of the waves is required for the production of electricity, so there are no relevant impacts associated with the consumption of raw material or other inputs, and the impact at this stage are those generated by the maintenance of the power plant.

Figure 2 shows that Construction is the life cycle stage with the highest associated environmental impacts for all the categories analyzed, followed by EoL. These results confirm two trends observed in wave energy generation systems: (i) the high environmental impacts associated with the use of materials in the Construction, and (ii) the importance of correct waste management at the EoL stage, since this could improve the environmental performance of the systems. These trends have been mentioned by other authors (Paredes et al. 2019; Uihlein 2016; Apolonia and Simas 2021; Parker et al. 2007; Thomson et al. 2019).

Figure 3 shows the environmental impacts associated with the Construction stage and two sub-stages: Breakwater and Power plant. It shows the Talus and foundations as part of the Breakwater sub-stage, while air chambers, turbine room, flooring and equipment are part of the Power plant sub-stage. Environmental impacts associated with the Breakwater sub-stage are between 6.87 and 49.44% for the different categories analyzed. Human Toxicity with $2.28E{-}03$ kg 1,4-DB eq/kWh is the category with the lowest impact and Particulate Matter Formation is the category with the higher impact ($2.80E{-}04$ kg PM_{10} eq/kWh) as shown in the Table 3. The impacts associated with the Talus component (4.78–49.08%), where MET with the lower impacts ($5.10E{-}05$ kg 1,4-DB eq/kWh) and PMF with the higher contributions ($2.78E{-}04$ kg PM_{10} eq/kWh), which are are divided into the concrete and limestone consumption. The construction of the Talus required large quantities of limestone, which is used for the nucleus of the seawall as well as the internal and external layers of the Breakwater. The estimated environmental impacts are between 61.8 and 98.4% for the consumption of limestone, and from 1.6 to 38.2% for the use of concrete. In both cases, the highest percentages of impacts are due to the category of PMF which, in the case of concrete, are mainly due to the transport of materials from one station to another, as well as their distribution by road, in addition to the clinkering process (Stafford et al. 2016),

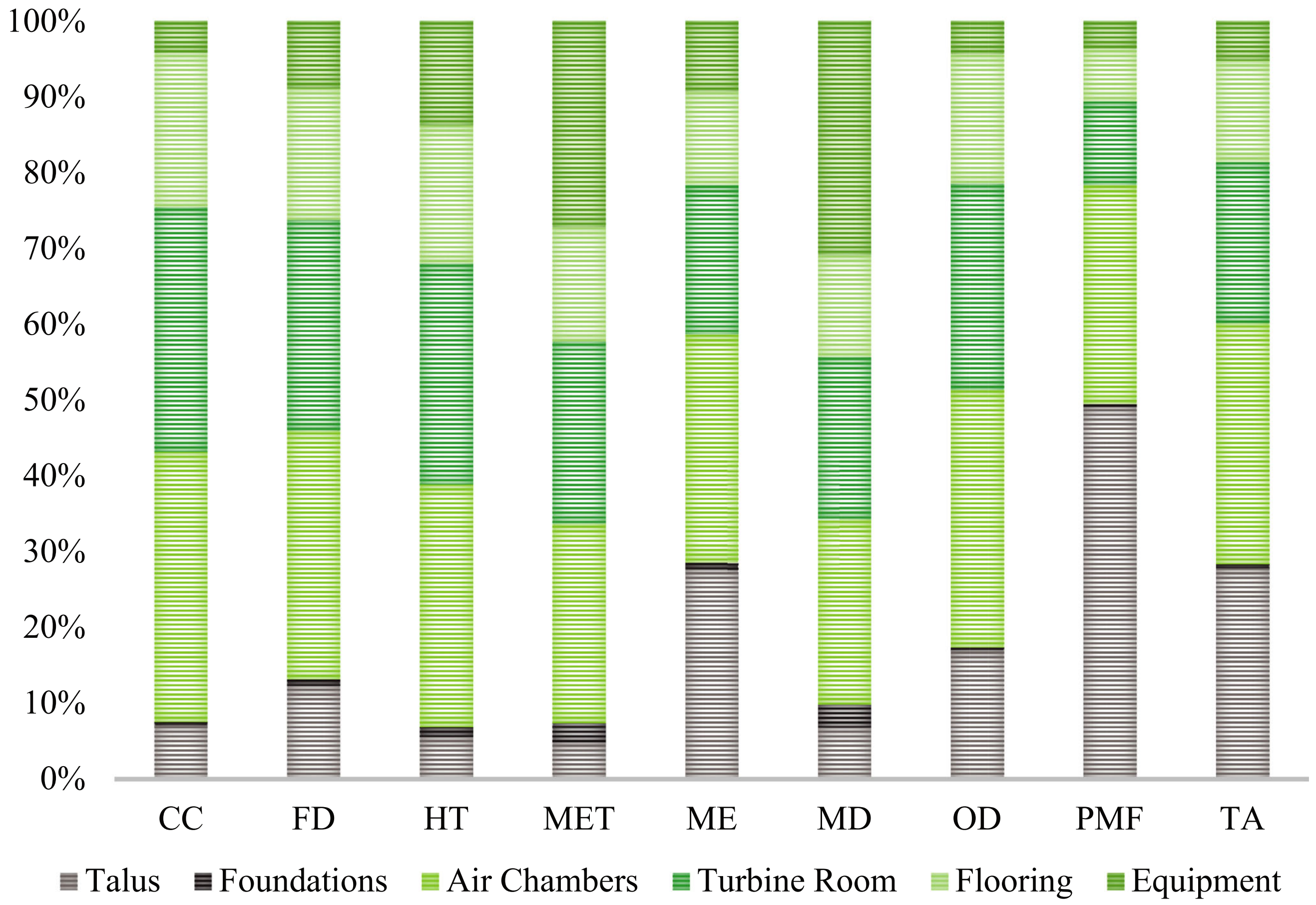

Fig. 3 Normalized and percentual LCIA profile of Mutriku wave energy power plant construction stage. CC: Climate Change. FD: Fossil Depletion. HT: Human Toxicity. MET: Marine Ecotoxicity. ME: Marine Eutrophication. MD: Metal Depletion. OD: Ozone Depletion. PMF: Particulate Matter Formation. TA: Terrestrial Acidification

while the impacts associated with limestone are due to its production. The impacts associated with the foundations (set of materials needed to keep the Breakwater fixed on the seabed) component, range from 0.4 to 3.0%, Climate Change represents the smallest percentage ($8.05E-04$ kg CO_2 eq/kWh) and Metal Depletion the largest ($2.35E-04$ kg Fe eq/kWh), which is to be expected since these impacts are entirely due to steel consumption, and as can be seen in the Fig. 3 it is the component that contributes with the lower impact in the Construction stage.

On the other hand, the rest of the impacts of the categories analyzed for the Construction stage are associated to the Power Plant sub-stage (51–93%), where the categories with the lowest and highest associated impact are PMF (2.86 kg PM_{10} eq/kWh) and HT ($3.09E-02$ 1,4-DB eq/kWh), respectively, as shown in Table 3. For this sub-stage, the Air Chambers component, is the largest contributor to environmental impacts for all categories (27–57%), except Metal Depletion where that minimum 27% of associated impacts represents an amount of $1.09E-03$ kg Fe eq/kWh, most of the impacts are due to the Equipment component (includes the materials required for the manufacture of the turbines), with 34% ($2.45E-03$ kg Fe eq/kWh), which is due to the consumption of steel for the manufacture of the Wells turbine; the next component with the highest impacts is Air Chamber with $1.94E-03$ kg Fe/kWh (27%), followed by Turbine Room (this means the space where the equipment inside the wave power generation plant is stored) that represents 24% ($1.70E-03$ kg Fe eq/kWh%) and Flooring with an amount of $1.07E-03$ kg Fe eq/kWh(15%).

The environmental impacts presented in Fig. 3, are consistent with the large quantities of raw materials required during the Construction stage in other studies (Uihlein 2016; Paredes et al. 2019. The processes of extracting and processing the resources needed to obtain these materials have considerable environmental burdens associated with them (Kittipongvises 2017). In the present research, concrete, limestone and steel are the three materials with the most significant contributions to environmental impact in all categories, where concrete presents the highest impacts. These impacts are associated with the large quantities of energy required by the cement industry, which are mostly provided by petroleum coke, which contributes to the generation of GHG; additionally, the clinker fabrication involves decarbonation reactions that generates CO_2 emissions.

Considering that the use of large amounts of concrete is common in ocean energy systems (Patrizi et al. 2019; Apolonia and Simas 2021; Dahlsten 2009), the environmental performance of the cement industry is a key factor to diminish the environmental footprint of the ocean energy systems. The impacts of the cement industry are due to the energy requirement needed to melt the raw material, since it is necessary to reach temperatures of around 1400 C in the kiln and this energy is provided by fossil fuels, mainly petroleum coke. In this sense, Güereca et al. (2015), mentions that to increase the environmental performance of the cement industry, as well as all those processes that involve this product, it is important to use alternative fuels such as the co-processing of inorganic waste with high calorific value. This is due to two main reasons: (1) reduce the use of petroleum coke, a fossil fuel that also requires a refining process, and (2) reduce the amount of waste that reaches landfills, minimizing the impact on the environment.

On the other hand, the impacts associated with limestone consumption in the categories of Climate Change (CC), Fossil Depletion (FD) and Human Toxicity (HT) are due to the extraction stage of materials and derive from the consumption of fossil fuels, such as gas oil, diesel and electric energy needed in the heavy machinery used for their extraction, transport and processing (Kittipongvises 2017).

Dahlsten (2009) mentioned that for wave energy systems, steel consumption could be between 30 and 80% of the environmental impacts. However, in this research these impacts are between 2.2 and 84.3% in the different categories analyzed. The above is due to factors such as the design of the device considered by Dahlsten (2009), which is a strut absorber type WEC whose manufacture is mainly of steel and iron, while the foundation of the present study is much smaller. In addition to being treated of a hypothetical wave energy plant, while the present study is a functional power plant.

Steel consumption is connected to the Construction stage and the impacts associated with it are mainly due to the extraction of raw materials such as cast iron, ferromagnesium and ferro-chromium (Douziech et al. 2016), as well as the use of fossil energy sources throughout the production chain. In the case of the climate change category, greenhouse gas emissions associated with steel production are directly due to the large amounts of energy required (mainly coke from mineral carbon), for the transformation of the iron ore to metallic iron and due to the coke fabrication (coking) (Burchart 2013; Olmez et al. 2016).

According to the last, it can be argued that if the concrete, limestone and steel are manufactured in cleaner industrial processes where the co-processing of waste, carbon sequestration or circular economy strategies are adopted, the wave energy systems can increase their contribution to the generation of affordable and clean energy (SDG 7) and to combat climate change (SDG 13).

On the other hand, the Generation stage has the lowest life cycle impacts. As shown in Fig. 4, the Rolling component is the major contributor to environmental impacts in almost all categories analyzed, with impacts between 21 and 92%, where the lower impact values correspond to Fossil Depletion ($1.12E{-}03$ kg oil eq/kWh) and the higher to Marine Ecotoxicity ($1.62E{-}04$ kg 1,4-DB eq/kWh). These impacts are associated with the consumption of metals such as aluminum and magnesium, as the production of metals throughout their supply chain gives rise to various environmental impacts directly associated with their extraction and processing, as well as indirectly associated with the use of raw materials, electricity consumption, and fossil fuels. In the case of aluminum, which is the metal with the highest percentage of associated impacts, two main processing stages for aluminum production are alumina refining and aluminum smelting (Halle-Heroult process) (Norgate et al. 2007). It is important to mention that between 5 and 6 Rollings are required per year, which contributes to the high impacts (Mutriku Wave Power Plant).

The second most important component in terms of the environmental impacts is the Fan. This is because of the consumption of thermoplastic, which is the main material used to manufacture the fans used in the Mutriku Wave Power Plant and of which approximately 5 units are required annually, as reported by the Mutriku Wave Power Plant Staff. The impacts associated with the Fan ranges from 0 to 73%, where Ozono Depletion genera the minimun impact with $8.09E{-}17$ kg CFC-11 eq/kWh and the higher is Fossil Depletion ($3.91E{-}03$ kg oil eq/kWh) due to the raw material and energy required by the supply chain of thermoplastic.

The environmental impacts from the remaining components are: Services between 4.2 and 57%, Bearing in a range of 0.4–9.4% and Lubricant between 0.1 and 3%. Services refers entirely to tap water consumed for different purposes, Bearing are associated to the steel required for the manufacture of these pieces, which are changed between 8 and 10 per year and the lubricant is used to grease all mechanical parts, which is used specially to ensure the functioning of the bearings, with a frequency of use of every 6 weeks (Mutriku Wave Energy Power Plant).

Figure 5 shows the LCIA for the EoL stage. There it can be observed that steel recycling avoids the environmental impact in six of nine analyzed categories. The most important benefits of steel recycling can be observed in the Metal Depletion

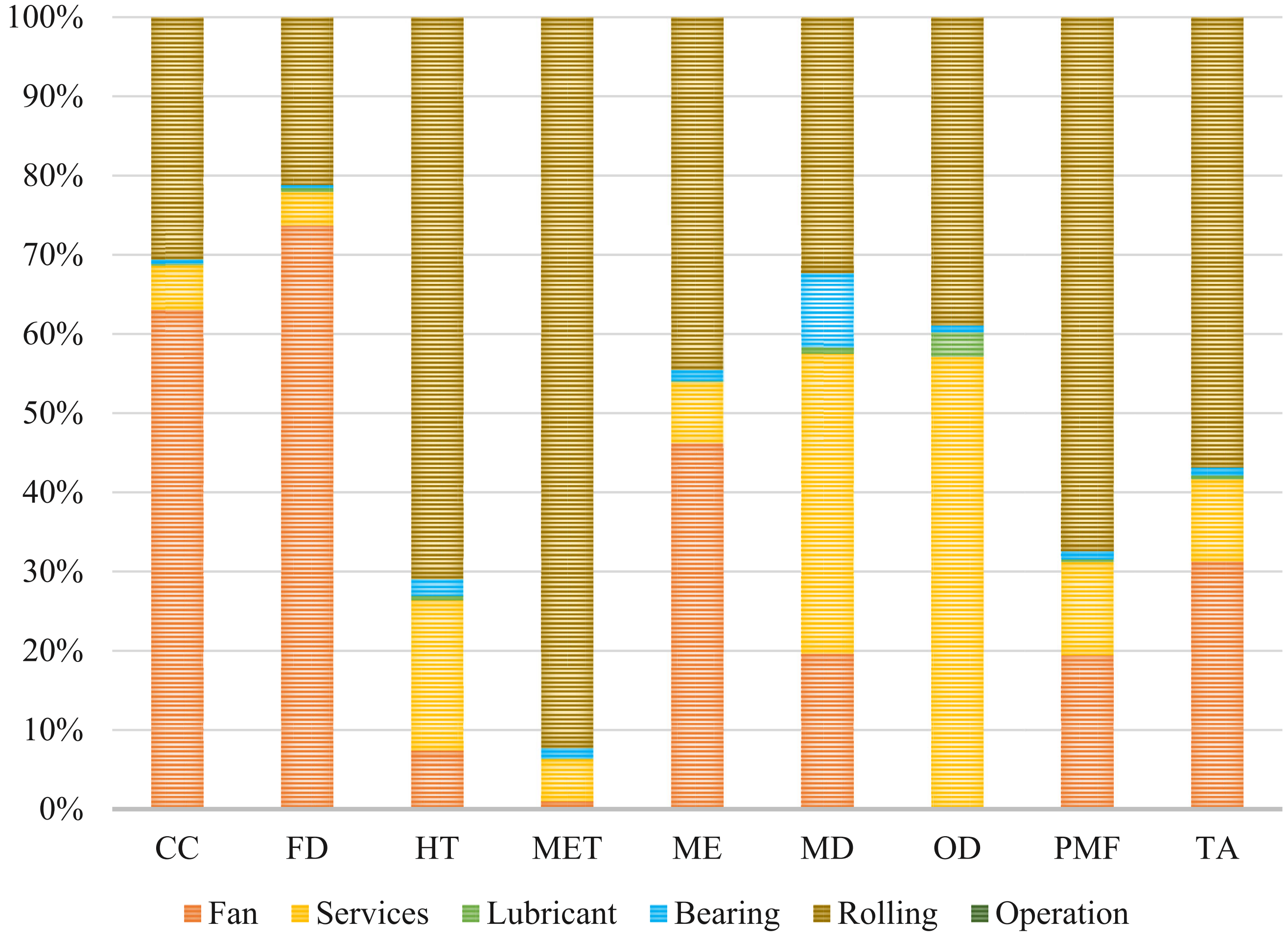

Fig. 4 Normalized and percentual LCIA profile of Mutriku wave energy power plant generation stage. CC: Climate Change. FD: Fossil Depletion. HT: Human Toxicity. MET: Marine Ecotoxicity. ME: Marine Eutrophication. MD: Metal Depletion. OD: Ozone Depletion. PMF: Particulate Matter Formation. TA: Terrestrial Acidification

(MD) category, followed by Climate Change, Fossil Depletion, Terrestrial Acidification, Human Toxicity, Particulate Matter Formation and Marine Eutrophication.

This reduction is consistent with other studies (Parker et al. 2007; Thomson et al. 2019). However, there could be more environmental impacts avoided if that recycled material in order to reduce the energy and raw material consumption (Dahlsten 2009).

The Concrete and the limestone disposed in Landfill have considerable environmental impacts in all the categories analyzed. This is because large quantities of these materials are required throughout the life cycle of the Mutriku wave power plant, especially in the Construction stage.

3.2 Sensitivity analysis of the EoL stage

Nowadays, the EoL is outside the operative boundaries in the ocean energy systems, mainly because this is a new industry (Apolonia and Simas 2021). The Table 4 shows the results of the LCIA for each one of EoL scenarios proposed for the different categories analyzed. As shown in Table 4, Steel Recycling, dimishes the environmental impact, except in the Ozone Depletion (OD) impact category, where E1 has the worst environmental performance. This isalso the case with the Steel Landfill Reducing the amount of waste arriving at the landfill results in lower impacts, which is in line with other research, which states that recycling has a positive impact by reducing stress at disposal sites and improving the environmental performance of the system (Paredes et al. 2019; Dahlsten 2009; Thomson et al. 2011).

Figure 6 shows the global normalized and percentual results for each of the proposed scenarios. It is observed that in 6 of the 9 categories analyzed, the influence of the different recycling rates is very small at the global level, since it varies between 0.13 and 0.53%. Similarly, it can be seen a great influence of the recycling rates on the global impacts of

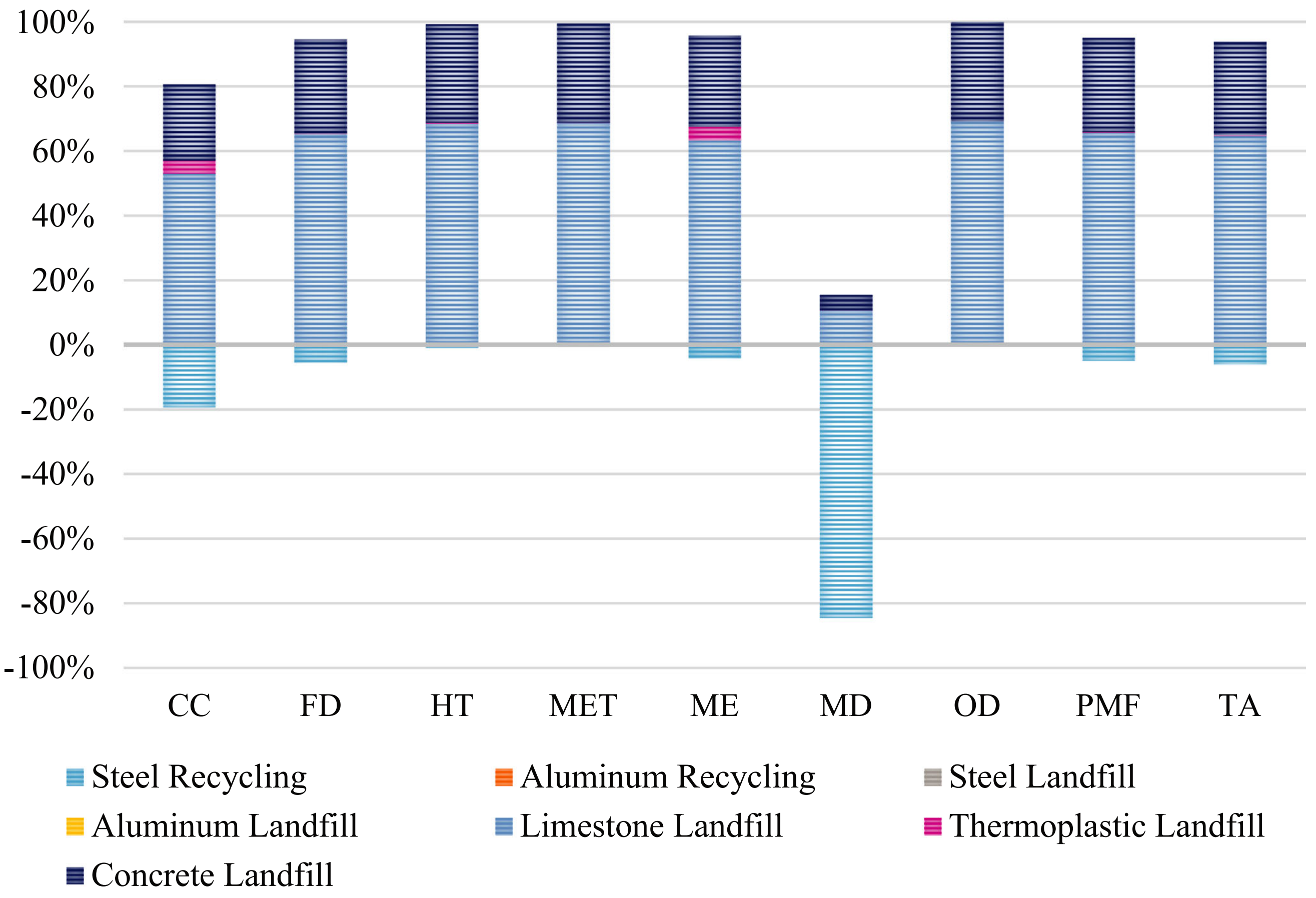

Fig. 5 Normalized and percentual LCIA profile of Mutriku EoL stage. CC: Climate Change. FD: Fossil Depletion. HT: Human Toxicity. MET: Marine Ecotoxicity. ME: Marine Eutrophication. MD: Metal Depletion. OD: Ozone Depletion. PMF: Particulate Matter Formation. TA: Terrestrial Acidification

each scenario in the MD category. For this category, as well as the other 6 mentioned before, the logical relationship "the higher the recycling rate (E1) the lower the environmental impacts" is satisfied.

In the MD category, the scenario with the lowest recycling rate (E3) accounts for 100% of the impacts, while E1 and E2, with recycling rates of 90% and 75% respectively, have 45.62% fewer impacts in E1 and 28.64% fewer impacts in E2, compared to E3. This is consistent with what is reported by Apolonia and Simas (2021), who concluded that for a wave energy system called MegaRoller, the variation in the recycling rates results in modest to significant changes in the overall results.

However, in the case of Human Toxicity (HT) and Marine Ecotoxicity (MET), the scenario E1, with the highest recycling rate, presents the highest impacts, related to the heavy metals, inorganic and organic compounds that are released into marine waters.

On the other hand, it was found that for all of the proposed scenarios, energy supplied by non-renewable sources is one of the main hot spots in Mutriku, where fuel oil is the main source of non-renewable energy used. This result is not new, since several authors have reported that the use of non-renewable energy sources minimizes the environmental performance of power generation systems through the ocean (Paredes et al. 2019; Pennock et al. 2021; Apolonia and Simas 2021).

For this reason, it is necessary to diversify the energy mix of each country in order to indirectly reduce the impacts associated with non-renewable energies and increase the environmental performance of renewable energies, in this case wave energy of the oscillating water column type, which is the system used in Mutriku power plant.

However, it is also reiterated that it is necessary to study new ways of including the environmental impacts of this type of wave energy extraction systems that are not contemplated within the life cycle analysis methodology. For the specific case of Mutriku, the environmental impacts generated by the change in the distribution of wave energy, in water circulation, in erosion patterns and sediment properties, as well as

Table 4 Environmental impacts assessment for each proposed EoL scenario and disposal site

Impact Categories	CC [kg CO2 eq.]	FD [kg oil eq.]	HT [kg 1.4-DB eq.]	MET [kg 1.4-DB eq.]	ME [kg N eq.]	MD [kg Fe eq.]	OD [kg CFC-11 eq.]	PMF [kg PM10 eq.]	TA [kg SO2 eq.]
Scenario E1									
Steel recycling	−5.66*E*−03	−1.31*E*−03	−3.71*E*−05	−6.65*E*−07	−2.84*E*−07	−6.04*E*−03	3.17*E*−11	−3.36*E*−06	−1.02*E*−05
Aluminum recycling	7.40*E*−12	−5.14*E*−12	1.34*E*−11	5.28*E*−13	−2.01*E*−15	8.50*E*−14	−2.43*E*−19	3.64*E*−14	−2.88*E*−13
Steel landfill	3.65*E*−05	1.30*E*−05	3.98*E*−06	1.23*E*−08	3.83*E*−09	8.63*E*−07	1.23*E*−19	3.38*E*−08	9.48*E*−08
Aluminum landfill	2.98*E*−06	1.06*E*−06	3.25*E*−06	1.00*E*−09	3.12*E*−10	7.03*E*−08	1.00*E*−19	2.75*E*−09	7.73*E*−09
Limestone landfill	1.54*E*−02	1.58*E*−02	3.24*E*−03	9.96*E*−05	4.32*E*−06	7.65*E*−04	7.72*E*−09	4.54*E*−05	1.09*E*−04
Thermoplastic landfill	1.18*E*−03	3.56*E*−05	1.12*E*−05	4.37*E*−08	2.91*E*−07	2.38*E*−06	3.38*E*−19	1.51*E*−07	4.03*E*−07
Concrete landfill	6.88*E*−03	7.03*E*−03	1.45*E*−03	4.44*E*−05	1.93*E*−06	3.41*E*−04	3.45*E*−09	2.03*E*−05	4.87*E*−05
Scenario E2									
Steel recycling	−4.72*E*−03	−1.09*E*−03	−3.10*E*−05	−5.54*E*−07	−2.37*E*−07	−5.04*E*−03	2.64*E*−11	−2.80*E*−06	−8.50*E*−06
Aluminum recycling	6.17*E*−12	−4.29*E*−12	1.12*E*−11	4.41*E*−13	−1.67*E*−15	7.09*E*−14	−2.03*E*−19	3.04*E*−14	−2.40*E*−13
Steel landfill	6.45*E*−05	2.30*E*−05	7.04*E*−06	2.17*E*−08	6.77*E*−09	1.53*E*−06	2.17*E*−19	5.98*E*−08	1.68*E*−07
Aluminum landfill	7.43*E*−06	2.64*E*−06	8.10*E*−07	2.50*E*−09	7.78*E*−10	1.76*E*−07	2.50*E*−20	6.88*E*−09	1.93*E*−08
Limestone landfill	1.54*E*−02	1.58*E*−02	3.24*E*−03	9.96*E*−05	4.32*E*−06	7.65*E*−04	7.72*E*−09	4.54*E*−05	1.09*E*−04
Thermoplastic landfill	1.18*E*−03	3.56*E*−05	1.12*E*−05	4.37*E*−08	2.91*E*−07	2.43*E*−06	3.38*E*−19	1.51*E*−07	4.03*E*−07
Concrete landfill	6.88*E*−03	7.05*E*−03	1.45*E*−03	4.44*E*−05	1.93*E*−06	3.41*E*−04	3.45*E*−09	2.03*E*−05	4.87*E*−05
Scenario E3									
Steel recycling	−3.14*E*−03	−7.28*E*−04	−2.06*E*−05	−3.69*E*−07	−1.58*E*−07	−3.36*E*−03	1.76*E*−11	−1.86*E*−06	−5.66*E*−06
Aluminum recycling	4.11*E*−12	−2.85*E*−12	7.42*E*−12	2.93*E*−13	−1.11*E*−15	4.72*E*−14	−1.35*E*−19	2.02*E*−14	−1.60*E*−13
Steel landfill	1.11*E*−04	3.97*E*−05	1.22*E*−05	3.97*E*−08	1.17*E*−08	2.63*E*−06	3.79*E*−19	1.03*E*−07	2.89*E*−07
Aluminum landfill	1.49*E*−05	5.29*E*−06	1.62*E*−06	5.00*E*−09	1.56*E*−09	3.51*E*−07	4.99*E*−20	1.38*E*−08	3.86*E*−08
Limestone landfill	1.54*E*−02	1.58*E*−02	3.24*E*−03	9.96*E*−05	4.32*E*−06	7.65*E*−04	7.72*E*−09	4.54*E*−05	1.09*E*−04
Thermoplastic landfill	1.18*E*−03	3.56*E*−05	1.12*E*−05	4.37*E*−08	2.91*E*−07	2.38*E*−06	3.38*E*−19	1.51*E*−07	4.03*E*−07
Concrete landfill	6.88*E*−03	7.05*E*−03	1.45*E*−03	4.44*E*−05	1.93*E*−06	3.41*E*−04	3.45*E*−09	2.03*E*−05	4.87*E*−05

CC: Climate Change. FD: Fossil Depletion. HT: Human Toxicity. MET: Marine Ecotoxicity. ME: Marine Eutrophication. MD: Metal Depletion. OD: Ozone Depletion. PMF: Particulate Matter Formation. TA: Terrestrial Acidification

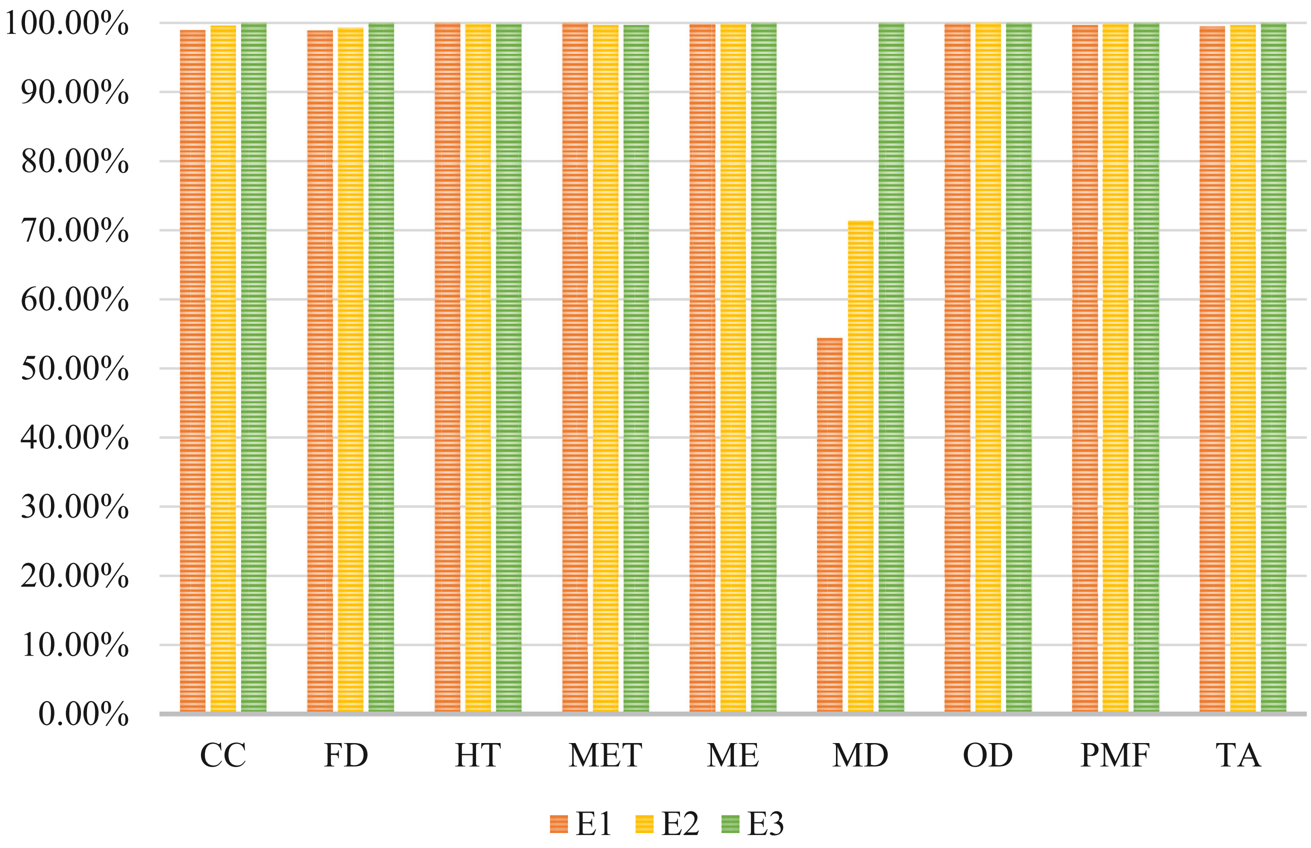

Fig. 6 Normalized and percentual LCIA for the proposed EoL scenarios of the Mutriku wave energy power plant. CC: Climate Change. FD: Fossil Depletion. HT: Human Toxicity. MET: Marine Ecotoxicity. ME: Marine Eutrophication. MD: Metal Depletion. OD: Ozone Depletion. PMF: Particulate Matter Formation. TA: Terrestrial Acidification

in the behavior, density and connectivity of the population of various species have been identified as relevant, and currently none of them can be evaluated with this methodology (Mendoza et al. 2019).

The most recurrent causes of environmental impacts due to raw materials used, is the consumption of fossil fuels as well as electricity, so the environmental performance of the Mutriku wave power plant depends largely on reducing the use of non-renewable energy sources. This has already been mentioned by Apolonia and Simas (2021), for the case of another wave energy system.

Although it is necessary to identify the different environmental impacts generated by ocean energy systems, and in this sense this research aims to increase knowledge on the topic, the climate change category remains as a relevant reference due to its importance, additionally, these results are easy to communicate and it is a topic with which decision makers are more familiar (Apolonia and Simas 2021). For this reason, Fig. 7 shows a comparison between different wave energy systems in terms of the climate change impact category.

As shown in Fig. 7, in the last fifteen years, there has been an increase in research about the environmental impacts of different wave energy systems. Of the16 LCA studies presented in Fig. 7, only 5 of them were conducted before or during 2011, therefore, 68.75% of the research done about wave energy systems under the LCA approach have been published in the last fifteen years. However, it has been a real challenge because ocean has a high theorical potential to produce electricity, but the technical potential is less, because of the many factors that challenge the use of this energy source such as the develop and efficiency of the devices, maintenance, investment costs or no public policy to encourage them (Sørense et al. 2006; Panwar et al. 2011; Tello and Marulanda 2017; Lund 2007; Bhat and Prakash 2009; Wilberforce et al. 2019; Montero and Calvo 2013).

In Fig. 7, it can be observed that there are large differences between the CO_2 equivalent emissions generated by the different devices reported in the literature for ocean energy. These differences result from several factors, mainly related to the materials required and accounted in the life cycle inventory, which are of critical importance because they depend both on the availability of data for each system and

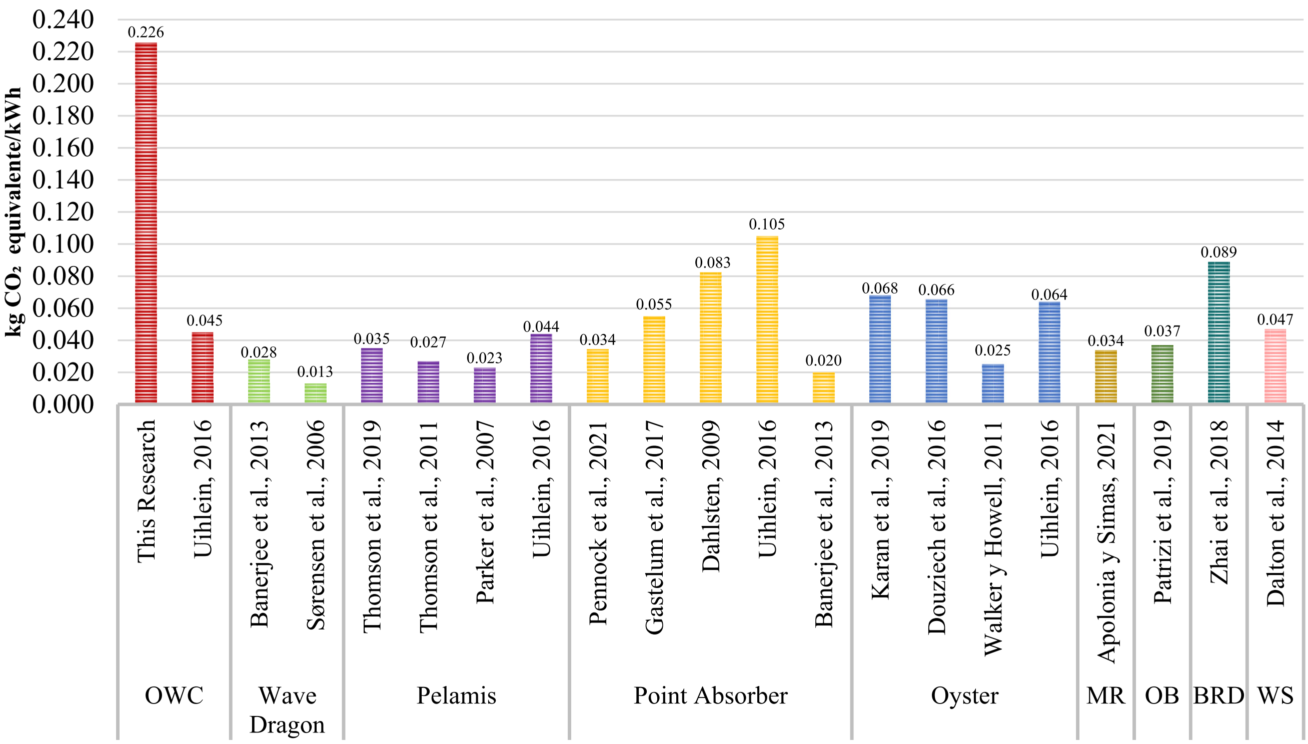

Fig. 7 Comparison of the climate change category of different technologies that produce energy from waves. OWC: Oscillating Water Column. MR: MegaRoller. OB: OBREC. BRD: Buoy Rope Drum. WS: Wavestar

on the assumptions made in each study. This is consistent with Banerjee et al. (2013), who suggest that greenhouse gas emissions are determined by the materials, and this is because these types of devices require large quantities of materials (Uihlein 2016).

On the other hand, the nominal capacity is another determining factor in the differences shown in Fig. 7, because it has been demonstrated that, in the case of power generation systems, the higher the generation of energy, the lower the impacts (Banerjee et al. 2013; Karan et al. 2019; Lenzen and Munksgaard 2002; Tremeac and Meunier 2009; Kadiyala et al. 2017). These factors, as well as the variety of designs, sizes and level of development, make it challenging to compare the different ocean energy systems fairly (Paredes et al. 2019; Douziech et al. 2016). In addition, there is limited knowledge of the long-term experience of several of these systems, since the lack of validated data on their generation phase (operation and maintenance) increases uncertainty (Pennock et al. 2021). In this sense, the research presented in this paper provides real information on the operation and maintenance of a commercial-scale plant with an OWC-type extraction system, helping to reduce the knowledge gap that exists today.

Similarly, it can be seen in Fig. 7 that Mutriku generates, compared to other ocean energy devices, between 53 and 94% more greenhouse gas emissions. However, it still has much better environmental performance than other technologies used in energy plants, as the case of a carbon power plant reported by Li et al. (2020), where 71% more emissions are generated than in Mutriku. For this reason, it can be affirmed that even with the challenges that ocean energy presents today, Mutriku was the right choice for the Basque Country to minimize the environmental impact of energy generation. It also emphasizes the need to implement mechanisms to facilitate research and development of ocean energy technologies and to implement policies that eliminate the economic disadvantages compared to conventional technologies (Wilberforce et al. 2019).

As mentioned by Uihlein (2016), and the detailed discussion in previous paragraphs, there is a lot of divergence between the design options for WECs. It is important to highlight that among the developments to improve the environmental performance of the devices, their efficiency must be increased (Paredes et al. 2019; Uihlein 2016).

As mentioned before, there is limited knowledge for the long-term experience of several of these systems, particularly inthe EoL stage where there is still not much information available on the best disposal options. For this reason, a sensitive analysis was performed with different recycling rates.

Additionally, to complement the discussion, the Energy Payback Time for Mutriku was estimated at 26.2 years, which represents the longest time when compared with the values reported by Aman et al, (2015), who reports 8 years for photovoltaics systems and 1.5 for wind energy systems. This difference can be explained because Mutriku represents a technology still in evolution.

4 Conclusions

In the Mutriku Wave Power Plant, Construction is the stage with the highest environmental impact of all the impact categories analyzed, while generation is the stage with the lowest impacts. This is mainly due to the fact that during the operation, no direct emissions are generated.

The wave energy systems can increase their contribution to the generation of affordable and clean energy (SDG 7) and to combat climate change (SDG 13), if the concrete, limestone and steel used in the Construction stage are manufactured in cleaner industrial processes where the co-processing of waste, carbon sequestration or circular economy strategies are adopted.

For the EoL stage, it was identified that steel recycling reduces environmental impacts in 6 of the 9 categories analyzed, resulting in a better environmental performance of the system. The final disposal of materials within the landfills has a considerable impact, mainly in the case of concrete due to the large quantities that were accounted for in the life cycle inventory.

On the other hand, the large quantities of concrete, limestone and steel used for the Construction stage imply relevant impacts for all the categories analyzed. For this reason, improvements in concrete and steel production processes—such as lower-carbon cement formulations, cleaner electricity mixes, or optimized structural design—could significantly reduce the life cycle impacts of similar wave energy facilities.

The climate change impact category resulted in $2.26E{-}01$ kg CO_2 eq per functional unit. When compared with fossil-based electricity generation systems reported in the literature, this value represents a substantial reduction in greenhouse gas emissions.

The sensitivity analysis performed for three different EoL scenarios shows that a higher recycling rate is not environmentally better for all recyclable materials.

Scenario E2 with a recycling rate of 75% of the metallic materials, presents the best environmental performance.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40722-026-00487-0.

Acknowledgements This research was funded by Consejo Nacional de Ciencia y Tecnología (CONACYT) and Secretaría de Energía (SENER): CONACYT-SENER/Sustentabilidad Energética Fund, through the Centro Mexicano de Innovación en Energías del Océano (CEMIE-Océano), grant number 249795. Additionally, the authors acknowledge to CONACYT for the scholarship awarded to Maria del Rosario León Lira.

Author contributions R.L.L. contributed with the execution of the LCA study and writing of the paper, J.L. worked in data integration and writing review and L.P.G. gave the conceptualization, main ideas, manuscript revision, supervision, writing review and funding acquisition. All authors read and approved the final manuscript.

Funding This research was funded by Consejo Nacional de Ciencia y Tecnología (CONACYT) and Secretaría de Energía (SENER): CONACYT-SENER/Sustentabilidad Energética Fund, through the Centro Mexicano de Innovación en Energías del Océano (CEMIE-Océano), grant number 249795. Additionally, the authors acknowledge to CONACYT for the scholarship awarded to Maria del Rosario León Lira.

Data availability The datasets generated during the current study are not publicly available due to confidentiality agreements, but could be available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose

References

Aman MM, Solangi KH, Hossain MS, Badarudin A, Jasmon GB, Mokhlis H, Bakar AHA, Kazi SN (2015) A review of safety, health and environmental (SHE) issues of solar energy system. Renew Sustain Energy Rev 41:1190–1204. https://doi.org/10.1016/j.rser.2014.08.086

Apolonia M, Simas T (2021) Life cycle assessment of an oscillanting wave surge energy converter. J Mar Sci Eng 9(2):206. https://doi.org/10.3390/jmse9020206

Arcelay I (2020) Análisis y comparativa de los parámetros de operación de las turbinas de la planta undimotriz de Mutriku en el periodo 2018–2019 (Bachelor's thesis). Engineering of Bilbao School, University of the Basque Country. Spain.

Banerjee S, Duckers L, Blanchard RE (2013) An overview on greenhouse gas emission characteristics and energy evaluation of ocean energy systems from life cycle assessment and energy accounting studies. J Appl Nat Sci 5(2):535–540

Bastos P, Devoy-McAuliffe F, Arredondo-Galeana A, Chozas JF, Lamont-Kane P, Vinagre PA (2023) Life cycle assessment of a lift-based wave energy converter. In: Proceedings of the European wave and tidal energy conference, vol 15, pp 1–10. University of the Basque Country (UPV/EHU). https://doi.org/10.36688/ewtec-2023-377

Bhat IK, Prakash R (2009) LCA of renewable energy for electricity generation systems: a review. Renew Sustain Energy Rev 13(5):1067–1073. https://doi.org/10.1016/j.rser.2008.08.004

Burchart DK (2013) Life cycle of steel production in Poland: a case study. J Clean Prod 54:235–243. https://doi.org/10.1016/j.jclepro.2013.04.031

Cascajo R, García E, Quiles E, Correcher A, Morant F (2019) Integration of marine wave energy converters into seaports: a case study in the Port of Valencia. Energies 12(5):787. https://doi.org/10.3390/en12050787

Crippa M, Guizzardi D, Pagani F, Banja M, Muntean M, Schaaf E, Becker W, Monforti-Ferrario F, Quadrelli R, Risquez Martin A, Taghavi-Moharamli P, Köykkä J, Grassi G, Rossi S, Brandao De Melo J, Oom D, Branco A, San-Miguel J, Vignati E (2023) GHG emissions of all world countries. Report. Publications Office of the European Union. Luxembourg. https://doi.org/10.2760/173513

Dahlsten H (2009) Life cycle assessment of electricity from wave power [Thesis]. Swedish University of Agricultural Sciences

Dalton G, Madden D, Clare MD (2014) Life cycle assessment of the wavestar. In: Ninth international conference on ecological vehicles and renewable energies (EVER), pp 1–9. Monaco Sustainable Development Association (MC2D) – IEEE. https://doi.org/10.1109/EVER.2014.6844065

Douziech M, Hellweg S, Verones F (2016) Are wave and tidal energy plants new green technologies? Environ Sci Technol 50(14):7870–7878. https://doi.org/10.1021/acs.est.6b01096

Ente Vasco de la Energía (2026) Energías marinas. Summary of Energy Data for the Basque Country, Spain. https://www.eve.eus/conoce-la-energia/la-energia-de-euskadi/datos-energeticos-euskadi/

European Commission (2020) An EU strategy to harness the potential of offshore renewable energy for a climate neutral future. (COM). Brussels, Belgium. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0741&from=EN

Faÿ F-X, Robles E, Marcos M, Aldaiturriaga E, Camacho EF (2020) Sea trial results of a predictive algorithm at the Mutriku wave power plant and controllers assessment based on a detailed plant model. Renew Energy 146:1725–1745. https://doi.org/10.1016/j.renene.2019.08.041

Fernández S (2017) Analizamos datos de la central undimotriz de Mutriku. Producción, factor de capacidad, problemas (Summary). Diario Renovables. https://www.diariorenovables.com/2017/12/central-undimotriz-de-mutriku-analisis-datos-produccion-problemas.html

Garrido AJ, Otaola E, Garrido I, Lekube J, Maseda FJ, Liria P, Mader J (2015) Mathematical modeling of oscillating water columns wave-structrue interaction in ocean energy plants. Math Probl Eng. https://doi.org/10.1155/2015/727982

Gastelum LZ (2017) Life cycle assessment of wave energy converter (Bachelor's thesis). KTH Royal Institute of Technology. Stockholm, Sweden. https://www.diva-portal.org/smash/get/diva2:1092837/FULLTEXT01.pdf

Guercio A, Kumar DM (2022) Life cycle assessment applied to a new system for sea wave energy harvesting. In: OCEANS 2022-Chennai. IEEE. Indian Institute of Technology Mandras (IIMT) – National Institute of Ocean Technology (NIOT) – IEEE Oceanic Engineering Society (OES) – Marine Technology Society (MTS). Chennai, Tamil Nadu, India. https://doi.org/10.1109/OCEANSChennai45887.2022.9775369

Güereca LP, Torres N, Juárez-López CR (2015) The co-processing of municipal waste in a cement kiln in Mexico. A life-cycle assessment approach. J Clean Prod 107:741–748. https://doi.org/10.1016/j.jclepro.2015.05.118

Ibarra GB, Sáenz J, Ulazia A, Serras P, Esnaola G, García CS (2018) Electricity production, capacity factor, and plant efficiency index at the Mutriku wave farm (2014–2016). Ocean Eng 147:20–29. https://doi.org/10.1016/j.oceaneng.2017.10.018

International Energy Agency (2023a) World energy outlook 2022. (Technical Analysis Report). Paris, France. https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf

International Energy Agency (2023b) CO_2 emissions in 2022. Technical Analysis Report. Paris, France. https://www.iea.org/reports/co2-emissions-in-2022

International Organization for Standardization (2006) Environmental management—Life cycle assessment—Principles and framework (ISO Standard No. 14040:2006). ISO. https://www.iso.org/standard/37456.html

IRENA (2025) Renewable energy statistics 2025. International Renewable Energy Agency. Abu Dhabi

Kadiyala A, Kommalapati R, Huque Z (2017) Characterization of the life cycle greenhouse gas emissions from wind electricity generation systems. Int J Energy Environ Eng 8(1):55–64. https://doi.org/10.1007/s40095-016-0221-4

Karan H, Thomson R, Harrison G (2019) Full life cycle assessment of two surge wave energy converters. Proc Inst Mech Eng A J Power Energy 234(4):548–561. https://doi.org/10.1177/0957650919869710

Kittipongvises S (2017) Assessment of environmental impacts of limestone quarrying operations in Thailand. Environ Clim Technol 20(1):67–83. https://doi.org/10.1515/rtuect-2017-0006

Lekube J, Ajuria O, Ibeas M, Igareta I, Gonzalez A (2018) Fatigue and aerodynamic loss in Wells turbine: Mutriku wave power plant case. In: Proceedings of the 7th international conference on ocean energy. EDP Sciences - French Research Institute for Exploitation of the Sea (IFREME) – Ocean Energy Systems. Cherbourg, France

Lenzen M, Munksgaard J (2002) Energy and CO_2 life-cycle analyses of wind turbines- review and applications. Renew Energy 26(3):339–362. https://doi.org/10.1016/S0960-1481(01)00145-8

Li H, Jian H-D, Dong K-Y, Wei Y-M, Liao H (2020) A comparative analysis of the life cycle environmental emissions from wind and coal power: Evidence from China. Journal of Cleaner Production. 248:119192

Lund H (2007) Renewable energy strategies for sustainable development. Energy 32(6):912–919. https://doi.org/10.1016/j.energy.2006.10.017

Mendoza E, Lithgow D, Flores P, Felix A, Simas T, Silva R (2019) A framework to evaluate the environmental impact of OCEAN energy devices. Renew Sustain Energy Rev 112:440–449. https://doi.org/10.1016/j.rser.2019.05.060

Montero JAS, Calvo JLR (2013) Energía maremotriz: perspectiva histórica y estado actual. Revista Técnica Industrial 304:42–49

Mustapa MA, Yaakob OB, Ahmed YM, Rheem CK, Koh KK, Adnan FA (2017) Wave energy device and Breakwater integration: a review. Renew Sustain Energy Rev 77:43–58. https://doi.org/10.1016/j.rser.2017.03.110

Norgate TE, Jahanshahi S, Rankin WJ (2007) Assessing the environmental impact of metal production process. J Clean Prod 15:838–848. https://doi.org/10.1016/j.jclepro.2006.06.018

Olmez GM, Dilek FB, Karanfil T, Yetis U (2016) The environmental impacts of iron and steel industry: a life cycle assessment study. J Clean Prod 130:195–201. https://doi.org/10.1016/j.jclepro.2015.09.139

Otaola E, Garrido AJ, Lekube J, Garrido I (2019) A comparative analysis of self-rectifying turbines for the Mutriku oscillating water column energy plant. Complexity. https://doi.org/10.1155/2019/4615971

Ozkan C (2020) The impacts of wave energy conversion on coastal morphodynamics in a changing climate (Doctoral dissertation).

Department of Civil, Environmental, and Construction Engineering. University of Central Florida. Orlando, Florida.

Panwar NL, Kaushik SC, Kothari S (2011) Role of renewable energy sources in environmental protection: a review. Renew Sustain Energy Rev 15(3):1513–1524. https://doi.org/10.1016/j.rser.2010.11.037

Paredes MG, Padilla AR, Güereca LP (2019) Life cycle assessment of ocean energy technologies: a systematic review. J Mar Sci Eng 7(9):322. https://doi.org/10.3390/jmse7090322

Parker RPM, Harrison GP, Chick JP (2007) Energy and carbon audit of an offshore wave energy converter. Proc Inst Mech Eng, Part a: J Power Energy 221(8):1119–1130. https://doi.org/10.1243/09576509JPE406

Patrizi N, Pulselli RM, Neri E, Niccolucci V, Vicinanza D, Contestabile P, Bastianoni S (2019) Lifecycle environmental impact assessment of an overtopping wave energy convert embedded in Breakwater systems. Front Energy Res 7:32. https://doi.org/10.3389/fenrg.2019.00032

Pennock S, Vanegas MC, Bloise TT, Jeffrey H, Dickson MJ (2021) Life cycle assessment of a point-absorber wave energy array. Renew Energy 190:1078–1088. https://doi.org/10.1016/j.renene.2022.03.118

Serras P, Ibarra GB, Sáenz J, Ulazia A (2019) Combining random forest and physics-based models to forecast the electricity generated by ocean waves: a case study of the Mutriku wave farm. Ocean Eng 189:106314. https://doi.org/10.1016/j.oceaneng.2019.106314

Sørense HC, Naef S, Anderberg S, Hauschild MZ (2006) Life cycle assessment of the wave energy converter: Wave Dragon. In: Proceedings of the international conference on ocean energy. OTTI ENERGI-KOLLEG – Ocean Energy Systems. Bremerhaven, Germany

Stafford FN, Raupp-Pereira F, Labrincha JA, Hotza D (2016) Life cycle assessment of the production of cement: a Brazilian case study. J Clean Prod 137:1293–1299. https://doi.org/10.1016/j.jclepro.2016.07.050

Tease WK, Lees J, Hall A (2007) Advances in oscillating water column air turbine development. In: Proceedings of the 7th European wave and tidal energy conference. Institute of Mechanical Engineering (DMEC) – Higher Technical Institute (IST) of Portugal. Oporto, Portugal.

Tello JM, Marulanda AG (2017) Modelo de optimización para sistemas de potencia en la evolución hacia redes inteligentes: una revisión. DYNA 84(202):102–111. https://doi.org/10.15446/dyna.v84n202.62577

Thomson RC, Chick JP, Harrison GP (2019) An LCA of the Pelamis wave energy converter. Int J Life Cycle Assess 24(1):51–63. https://doi.org/10.1007/s11367-018-1504-contempt

Thomson RC, Harrison GP, Chick JP (2011) Full life cycle assessment of a wave energy converter. In: Proceedings of the IET conference on renewable power generation (RPG 2011). The Institution of Engineering and Technology. Edinburgh, UK. https://doi.org/10.1049/cp.2011.0149

Torre-Enciso Y, Marqués J, López de Aguileta LI (2010) Mutriku: lessons learnt. In: Proceedings of the 3rd international conference on ocean energy. Basque Energy Agency (EVE) - Tecnalia – Ocean Energy Systems. Bilbao, Spain. https://www.ocean-energy-systems.org/publications/icoe/icoe-2010/document/mutriku.-lessons-learnt/

Torre-Enciso Y, Ortubia I, López de Aguileta LI, Marqués J (2009) Mutriku wave power plant: from the thinking out to the reality. In: Proceedings of the 8th European wave and tidal energy conference, vol 710, pp 319–329. Uppsala University. Uppsala, Sweden. https://tethys.pnnl.gov/publications/mutriku-wave-power-plant-thinking-out-reality

Tremeac B, Meunier F (2009) Life cycle analysis of 4.5 MW and 250 W wind turbines. Renew Sustain Energy Rev 13(8):2104–2110. https://doi.org/10.1016/j.rser.2009.01.006

Uihlein A (2016) Life cycle assessment of ocean energy technologies. Int J Life Cycle Assess 21(10):1425–1437. https://doi.org/10.1007/s11367-016-1120-y

Vicinanza D, Lauro ED, Contestabile P, Gisonni C, Lara JL, Losada IJ (2019) Review of innovative harbor breakwaters for wave-energy conversion. J Waterw Port Coast Ocean Eng 145(4):03119001. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000519

Walker S, Howell R (2011) Life cycle comparison of a wave and tidal energy device. [Doctoral dissertation]. University of Sheffield. Sheffield, United Kingdom.

Wilberforce T, El Hassan Z, Durrant A, Thompson J, Soudan B, Olabi AG (2019) Overview of ocean power technology. Energy 175:165–181. https://doi.org/10.1016/j.energy.2019.03.068

Zhai Q, Zhu L, Lu. S (2018) Life cycle assessment of a buoy-rope-drum wave energy converter. Energies 11(9):2432. https://doi.org/10.3390/en11092432