D6.2

Life Cycle Assessment

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Executive summary

This deliverable contains the results obtained from the Life Cycle Assessment (LCA) of the tidal turbine blades developed in the NEMMO project, as well as the LCA of two tidal energy farms where the turbines use the project blades. To develop this analysis, the methodology described in the ISO 14040:2006 and 14044:2006 standards was applied.

The main objectives of this deliverable can be summarised as follows:

- Carrying out a life cycle inventory analysis by quantifying all the energy and material flows, as well as the incoming and outgoing materials (extracted or emitted into the environment) required during the manufacturing processes of the components of the tidal energy farms and their useful life, paying special attention to the life cycle of the turbine blades.
- Calculation of the most relevant environmental impact indicators associated with tidal energy generation and the blades developed in the project to be compared with other existing systems.

In this sense, the tidal energy farms analysed have the following characteristics:

- Scenario 1: A 34.5 MW installed capacity tidal energy farm, consisting of 23 platforms of 1.5 MW each.
- Scenario 2: A theoretical tidal energy farm of 100 MW of installed capacity composed of 30 platforms of 3.3 MW each.

As main conclusions from this study, the environmental impacts of one kWh generated in each of the tidal farms, measured through four of the environmental indicators recommended by the European Commission in the PEF methodology application guide, are shown in the following table. In the first scenario, the generation of each kWh generates 40.40 g of CO_2eq, while in scenario 2, this value is reduced up to 22.41 kg CO_2eq. The reason for this fact is that the system analysed in the first scenario is not fully optimised, as it is the scenario tested after incorporating the innovations carried out in the NEMMO project. However, scenario 2 represents a more optimized hypothetical tidal energy farm.

TABLE 1. RESULTS, PER KWH OF ELECTRICITY, IN THE TWO SCENARIOS COSNIDERED IN THIS STUDY

	Units	Scenario 1	Scenario 2
Climate change	g CO_2 eq / kWh	40.40	22.41
Ecotoxicity, freshwater	CTUe / kWh	2059860	1517010
Land use	Pt / kWh	229050	130160
Water use	m^3 depriv. / kWh	11030	6230

Of all the factors that determine the environmental impacts caused by each kWh of electricity generated in a tidal energy farm, the impact caused by the materials needed to build the structure of the floating platforms and the mooring systems are the most important. Regarding the impacts of the tidal stream turbine blades, most of the impacts are caused by the production of the materials used in the manufacture of the blades. For this reason, one of the future challenges facing the tidal energy industry now is to improve the recyclability of composite material blades at the end of their useful life. This fact would significantly reduce the environmental impact of the electricity produced and increase the circularity of the materials. In addition, it would be advisable to eco-design the components that form part of tidal energy farms, especially the floating platforms and the mooring systems, in order to reduce the amount of material required and reduce the environmental impact of the farms without affecting their operability.

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Abbreviations

AWARE: Available WAter Remaining.

BOF: Basic Oxygen Furnace.

CFC-11: Trichlorofluoromethane.

CM.I: Core Module. Infraestructure.

CTUe: Comparative Toxic Unit ecotoxicity.

CTUh: Comparative Toxic Unit for human.

EC: European Comission.

ELCD: European Life Cycle Database.

EoL: End-of-Life.

EPD: Environmental Product Declaration.

ETH: Eidgenössische Technische Hochschule (Swiss Federal Institute of Technology in Zurich).

FU: Functional Unit.

GHG: Greenhouse Gases.

IPCC: Intergovernmental Panel on Climate Change.

ISO: International Organization for standarization.

JRC: Joint Research Center.

LCA: Life Cycle Assessment.

LCI: Life Cycle Inventory.

LCIA: Life Cycle Impact Assessment.

NMVOC: Non-methane volatile organic compounds.

PCR: Product Category Rules.

PEF: Product Environmental Footprint.

PPP: Polluter Pays Principle.

PTO: Power Take Off.

UM: Upstream Module.

UN: United Nations.

WP: Work Package.

1. Introduction

Considering the importance of the development of renewable sources of energy to meet future energy demands while supporting the transition of the European economic growth away from fossil fuels and, thus, mitigating climate change, different renewable energy technologies and innovations are under development. Among them, tidal energy is considered as one of the most efficient recent technologies. The reasons for such a consideration are various: tidal energy is unlimited, everlasting, and less susceptible to climate change and climate changes, energy can be produced day and night, tidal currents can be replicated, the resulting power can be predicted and it has a high efficiency comparing it to other energy sources [1].

The NEMMO project aims at supporting the development of a breakthrough tidal energy technology by generating the necessary models, knowledge, designs, and testing procedures to develop larger, more efficient, and more durable composite tidal turbine blades. These blades are based on advanced composite material featuring nano-reinforced and antifouling bio-mimetic characteristics, which is expected to increase their performance.

The above-mentioned performance has been tested in different workpackages of the NEMMO project and specifically under *WP6 – Cross-cutting activities*. Which aims, on the one hand, at analysing the environmental impacts of the proposed tidal energy technologies during their whole life cycle, providing solutions for minimizing the identified hotspots; and on the other hand, at validating the designed tidal turbines through a techno-economic and social assessment. Finally, a strategy for overcoming possible barriers, oriented to improve the environmental performance in future developments, has been defined.

This report focuses on the environmental impacts' analysis. Results of a conducted Life cycle assessment (LCA) are presented, with the objective of determinig the environmental impacts and potential hotspots of the innovative design of tidal turbine blades resulting from the research activities within the framework of the project NEMMO. The adopted methodology follows the International Standards Organisation (ISO)´s general standards on LCA, namely: ISO 14040:2006 and ISO 14044:2006. According to ISO 14040, the procedure consists of the compilation of relevant inputs and outputs of a product system, the evaluation of the potential environmental impacts of the relevant inputs and outputs, as well as, the interpretation of the results.

This deliverable aims at presenting a LCA, compliant with international standards (ISO 14040 and ISO 14044), thus determining the environmental impact and potential hotspots of the selected scenarios:

- 34.5 MW installed capacity tidal farm made up of 23 platforms of 1.5 MW floating tidal turbines

- 100 MW installed capacity tidal farm made up of 30 platforms of 3.3MW floating tidal turbines

Regarding the data compilation and in order to ensure a consistent environmental analysis, feedback from partners and specialised sources of information on tidal energy and innovative materials has been gathered. This data collection has been the basis for the definition of the inventory analysis, where raw materials, energy and waste flows associated to the whole life cycle of the NEMMO system have been considered. Subsequently, potential environmental impacts have been evaluated throughout the whole life cycle, to conclude with the interpretation of the results, where the assessments of selected technologies are presented.

The rest of this report is structured as follows: section 2 describes the NEMMO tidal energy concept (i.e. The Magallanes floating system), section 3 defines the methodological approach considered for the consecution of the LCA; section 4 analyses the goal and scope of the study; section 5 introduces the LCI that is detailed in Appendix B; section 6 contains a summary of the life cycle impact assessment (LCIA); and section 7 presents the most significant conclusions obtained after the analysis.

2. The Magallanes floating system

A full description of the system modelling definitions, boundaries and Life Cycle Inventory has already been presented to the European Commission as part of D6.1. System Modelling (Confidential, approved). As a summary, this section, presents a description of the NEMMO tidal energy concept that is being subject of the environmental assessment in this report, so that it is self-contained and easier to follow by the reader.

The floating system (ATIR device) developed by Magallanes is based on a steel-built trimaran, hereinafter called *platform,* which incorporates a submerged part where the hydrogenators are fitted (Figure 1). The 45-metre floating platform is suited with two 21-metre-high counter-rotating three-bladed rotors situated below the hull, which combined can produce up to 1.5MW. As the platform floats, it does not involve any construction on the sea bottom and installation and decommissioning can be easily done. The movement of the rotors is transformed into mechanical energy which is subsequently converted into electricity by a generator. The blades have a variable pitch system to allow blade configuration and pitch to change according to the current. A powerful control system manages the onboard systems and enables remote connection and communications with the platform. The engineering of the hull and its construction comes from the Naval industry, and all the machinery inside is supplied by the windmill sector. Among other advantages, the platform is also designed so that any maintenance or repair can be done from the inside of the platform, giving access to the machinery room 15 metres below sea level.

FIGURE 1: MAGALLANES TIDAL ENERGY PLATFORM

As shown in Figure 2, the platform can be broken down in the following blocks: upper block, vertical block (or mast) and lower block (or nacelle).

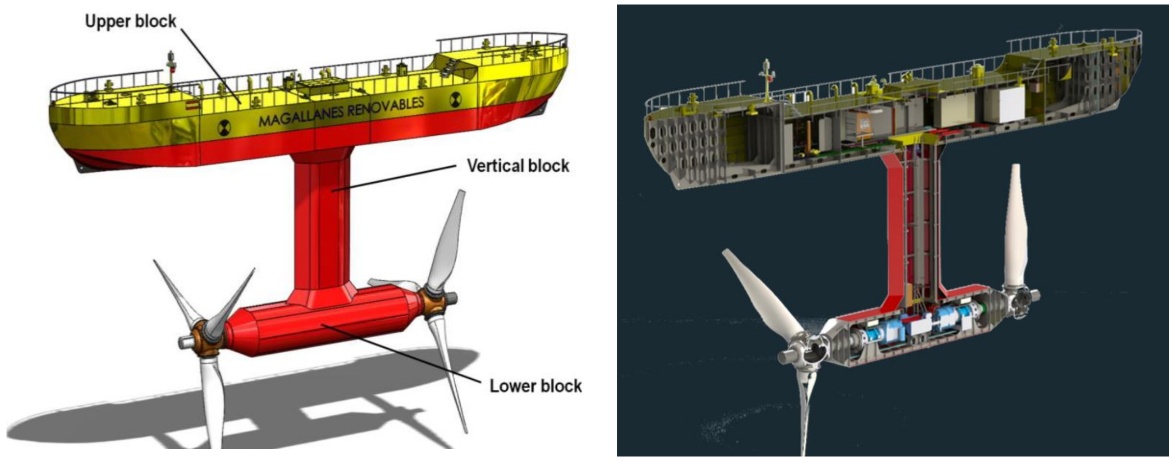

FIGURE 2: SCHEME OF PLATFORM BLOCKS DISTRIBUTION

UPPER BLOCK

It is the visible block of the platform, as around a half of it is above the waterline. It is the block through which the platform is accessible for maintenance. It 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. Apart from these three main rooms, there are two inaccessible compartments at both ends of the block which are part of the ballast system which employs fresh water treated, as well as several tanks in the centre of the block for environmental acceptable lubricant supply and bilge water.

VERTICAL BLOCK (mast)

Fixes the lower block to the upper block. It is a hollow space through which the communication and low-voltage cables connect the equipment housed in the lower block with the parts of the systems within the upper block. Rigid pipes for environmental acceptable lubricant supply and draining, among others, are also installed in the vertical block.

LOWER BLOCK (nacelle)

It is significantly smaller than the upper block and it is devoted to the mechanical system. The most relevant components placed in this block are the main shafts, ball bearings, gear boxes and generators. As it had been indicated before, the platform is fitted with two counter-rotating rotors. As a result, all components of the mechanical system shall be in duplicate (one for each rotor).

A scheme related to the mechanical system for one of the rotors is illustrated in Figure 3.

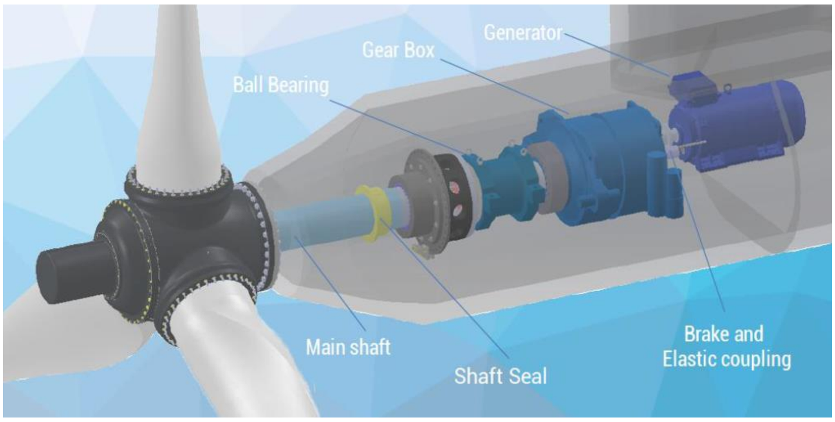

FIGURE 3: MAIN COMPONENTS OF THE MECHANICAL SYSTEM

The rotor system consists of 4 main components, which are the blades, the variable pitch system, the main shaft, and the bearings. The mechanical system for the other rotor is identical, but installed oppositely, in the other end of the lower block. Out of the lower block but aligned with the main shaft is the hub with **the three blades**, comprising the rotor. The blades are one of the main elements of the NEMMO project and their manufacturing has been subject of a specific LCA, as detailed in section **5.1.1**. There are three blades in each turbine, and each platform containing two turbines. The components of each NEMMO blade include fibre glass reinforced polyester (56%), resin (39%), gel coal (1%) and adhesives (3%).

The platform is anchored to the sea bottom by four mooring lines, two in the bow and two in the stern. 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 the platform is transmitted first through an umbilical cable and then through EMEC's subsea cables to EMEC's shore-based substation for onward transmission to the National Grid.

3. Methodological approach

This section describes the methodolgy followed for undertaking the environmental asessment. The LCA methodology seeks to evaluate the environmental performance during the whole life cycle of products and services, from raw material extraction, through energy and material production, to use and end-of-life treatment. This metholology has been developed due to the growing awareness and willingness to boost the environmental protection.

The LCA methodology used in this deliverable is based on the following 2 standards:

- ✓ ISO 14040:2006 - Environmental management -- Life cycle assessment -- Principles and framework (ISO, 2006a) [2].
- ✓ ISO 14044:2006 - Environmental management -- Life cycle assessment -- Requirements and guidelines (ISO, 2006b) [3].

The LCA carried out within NEMMO project has been developed according these standards.

The accomplishment of a LCA provides the following opportunities to interested stakeholders:

- ✓ To improve the environmental performance of products at various points in their life cycle.
- ✓ To inform decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign).
- ✓ To select relevant indicators of environmental performance, including measurement techniques.
- ✓ To use it as marketing tool (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

According to the ISO 14040, there are 4 different phases to conduct a LCA study:

1. **The goal and scope definition phase:** In this phase, the reasons for carrying out the study (goal) and the product system (scope) are defined. In doing so, whether the results are used for comparative reasons or not, the intended audience, functional unit (reference to which the inputs and outputs are related), system boundaries (unit processes to be included in the system considering all life cycle stages), allocation procedures, impact categories, as well as, system assumptions need to be determined.
2. **The inventory analysis phase:** This phase implies the data collection (at all life cycle stages) and determination of calculation procedures to quantify relevant inputs and outputs of a system. Related data are raw material and energy inputs, products/co-products, waste, and emissions, and it must be related to unit processes and reference flow of the functional unit. Collected data must be validated.
3. **The impact assessment phase:** This phase aims at evaluating the environmental impacts considering the cata collected during the inventory analysis phase. For that, inventory data must be associated with the environmental impact categories and indicators. Mandatory steps within this phase are:
    - Selection of impact categories, category indicators and characterization models.
    - Assignment of LCI results.
    - Calculation of category indicator results (characterization).

   According to ISO, optional steps are: normalization, grouping and weighthing of results.
   If necessary, the goal and scope can be updated within this phase.
4. **The interpretation phase:** In this phase, the results consistent with previously defined goal and scope are presented. The aim is to generate a set of conclusions, limitations of the study and recommentations to decision-makers.

Figure 4 shows how different phases in a LCA interact with each other.

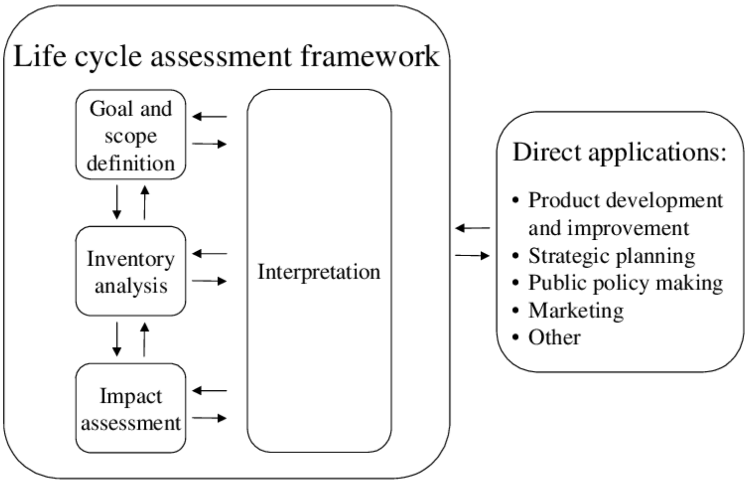

FIGURE 4. STAGES OF A LIFE CYCLE ASSESSMENT (ISO 14040)

4. Goal and scope definition of the study

The goal of the LCA presented in this deliverable is to assess the environmental impacts caused by the production of electricity in two different scenarios of the NEMMO tidal system, identifying main hotspots and providing a benchmark comparison with other tidal technologies. In addition, the study will pay special attention to the impacts caused by the proposed blade design throughout their life cycle, which are expected to contribute to a breakthrough in ocean tidal energy.

On the one hand, the environmental impacts associated with the manufacture, use and end-of-life of the equipment and infraestrucutre needed to generate tidal electricity are calculated. On the other hand, the impacts associated with each kWh of electricity generated are analysed to facilitate the comparison of the impacts of this novel technology with those of other tidal energy systems.

4.1. Target audience

The status of this deliverable is public and therefore, the main target audience are the partners of the NEMMO project and the European Commission, as well as the different stakeholders who promote the development of tidal energy technologies in general and of blades in particular, and who may be interested in knowing the related environmental impacts.

4.2. Scope of the study

Two different NEMMO tidal farm scenarios are be assessed in the project:

- ✓ **Scenario 1**: A 34.5 MW installed capacity scenario consisting of 23 platforms of 1.5 MW each. The selected geographical location for this system is Wales, where Magallanes Renewables S.L is planning to install 30MW of tidal capacity by 2024 as part of the Morlais project. However, the construction of this tidal farm is a longer-term project. Until it is built, data has been obtained from a real operating system with similar characteristics installed on the island of Orkney in Scotland.
- ✓ **Scenario 2**: A theoretical scenario of 100 MW of installed capacity composed of 30 platforms of 3.3MW each, whose data will be extrapolated from Scenario 1. The selected location of this farm is also the same as in scenario 1.

Based on these scenarios, the following functional units and system boundaties have been stablished.

4.3. Functional unit

The functional unit (FU) provides a reference for inputs and outputs within a product system, and it is required to ensure that comparations are being made under a common basis.

The functional unit used as a common reference for reporting the results in this LCA is ***the generation of one kWh of electricity produced with the Magallanes tidal system*** at the output of the tidal farm, in each of the two tidal farm scenarios defined in the previous section.

4.4. System boundaries

The system boundaries of the LCA performed in this report include the analysis of the tidal energy converter technology considered in the NEMMO project and its incorporation into two theoretical tidal energy farm scenarios. To define the boundaries of this analysis, the recommendations given by the Product Category Rules document "electricity, steam and hot/cold water generation and distribution" [4], developed in the framework of the International EPD® System, has been considered.

For the quantification of the environmental impact, a "cradle to gate" approach is applied. To do so, all impacts involved in the average production of a net kWh of electricity will be calculated, considering the impacts of the tidal farm up to the point of connection to the grid.

According to [4], the analysis is divided into the study of three different modules: Upstream module, core module and downstream module. The stages involved in each of these modules are detailed below.

- **Upstream module**

This module 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 oils, antifouling paint and other consumables, as well as the emissions from the transport of these substances from the suppliers to the tidal energy farm.

- **Core module (I): infrastructure**

The infrastructure module covers all stages related to the construction and decommissioning of the tidal energy farm, from cradle to grave. It includes all stages, from the extraction of the raw materials necessary for the construction of the tidal energy platforms, mooring systems and electrical systems, to 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. In this sense, the analysis of this infrastructure needed for the NEMMO technology has been done following a cradle-to-grave approach.

This module also covers the manufacturing processes of the innovative blades developed in the NEMMO project. It also includes the corrective maintenance actions foreseen for the equipment during its useful life (estimated component replacements and repairs). All environmental impacts arising from the transport of the above concepts to the tidal energy farm are also part of the core module.

- **Core module (II): operation**

In this module, all environmental impacts associated with the operation of the tidal energy farm throughout its lifetime will be considered. On the one hand, this module includes 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. In addition, the factors that determine the performance of the turbines are considered, such as annual energy production, machine availability, losses during operation or the self-consumption of energy from the turbine for its auxiliary systems.

In Figure 5, system boundaries diagram of both core modules is presented:

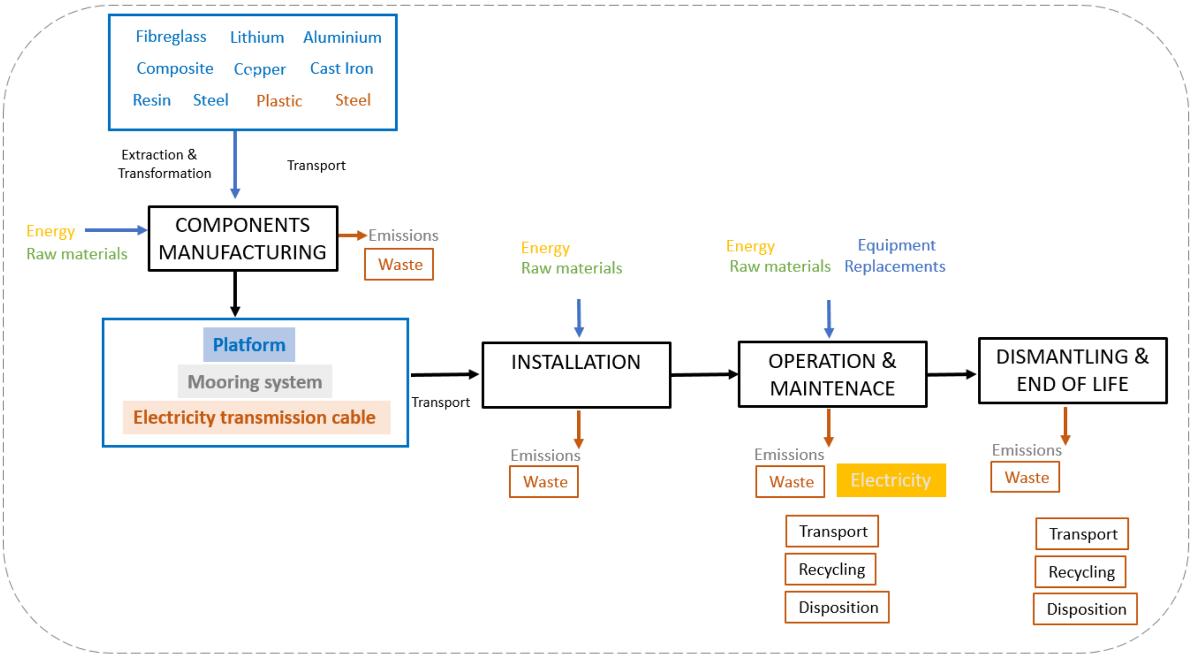

FIGURE 5. SYSTEM BOUNDARY DIAGRAM OF THE MAGALLANES TIDAL FARM

- **Downstream module**

Finally, following the scheme proposed by the International EPD System, the downstream module comprises all the impacts that occur from the point where the energy is delivered to the electricity grid (thus leaving the tidal energy farm) until it reaches the final consumer.

The downstream module represents mainly two different environmental impacts. On the one hand, the first one is the impact related to the construction and decommissioning of the electricity grid. On the other hand, the second impact is related to the electrical losses inherent to voltage transformations and the Joule effect in the transport of the electricity generated.

In the study carried out in this deliverable, the downstream module is not considered, as there is no variation in these stages associated with the innovations developed in NEMMO project. Therefore, the functional unit considered in the study is one kWh of electricity at the output of the tidal farm, instead of a kWh delivered to the final consumer as indicated in the PCR of the International EPD System.

On the other hand, the electricity generated during the entire life cycle of the Magallanes tidal system was considered. The impacts generated by the generation of each kWh of electricy were calculated and then compared to the impact of other enegy generation systems..

Regarding geographical and temporal boundaries, the results are representative for the corresponding geographical areas and time period (e.g. Wales and 2021). Other LCA studies carried out in different countries or regions and in different time may be not comparable to the results obtained in this study.

4.5. Cut-off criteria

The cut-off criteria specify the amount of material, energy flow or level of environmental significance associated with the product system that will be excluded from the study. This must be defined clearly.

To ensure a comprehensive analysis of the environmental performance of this technology, the material and energy inputs excluded from this analysis do not represent more than 3 % of the cumulative mass of the NEMMO core system. This cut-off criterion is in line with the recommendations given by the EC in the PEF methodology[5].

4.6. Allocation criteria

The allocation rules will deal with multifunctionality and the impact categories that must be calculated during the impact evaluation phase later in the study. It was considered that the electricity is the only product generated by the process under study. Therefore, all the impacts generated by the producction process have been attributed to the generated electricty.

On the other hand, the methodological choices for allocation for reuse, recycling and recovery have been set according to the polluter pays principle (PPP). This means that the generator of the waste that pays for its disposal shall carry the full environmental impact until the point in the product's life cycle at which the waste is transported to a scrapyard or the gate of a waste processing plant (collection site). The subsequent user of the waste shall carry the environmental impact from the processing and refinement of the waste but not the environmental impact caused in the "earlier" life cycles. On this basis, for example, no credits (negative flows) have been applied as an output based on recycling rates when modelling EoL stages in NEMMO.

4.7. Data-quality assessment

Based on the source of the data, the information included in the LCI can be classified into three categories [4]]:

- Specific data (or primary data): data gathered from the actual manufacturing plant where product-specific processes are carried out and data from other parts of the life cycle traced to the specific product system under study.
- Generic data (or secondary data), divided into:
  - selected generic data – data from commonly available data sources (e.g., commercial databases and free databases) that fulfil prescribed data quality characteristics for precision, completeness, and,
  - proxy data – data from commonly available data sources (e.g., commercial databases and free databases) that do not fulfil all the data quality characteristics of "selected generic data".

As a rule, specific data shall always be used, if available. If specific data is not available, generic data may be used, but they must be as representative as possible.

4.8. Impact categories and impact assessment

The selection of impact categories and characterization methods should be coherent with the goal and scope, so that the results obtained should answer the questions that motivated the analysis. In this sense, the ISO 14040 recommends employing categories and methods which are internationally accepted, scientifically and technically valid and environmentally relevant, trying to harmonize this kind of analysis.

For this reason, this LCA study was carried out considering the quantification of the environmental indicators proposed by the European Commission in the publication "Recommendation on the use of Environmental Footprint methods" [5]. The objective of those suggestions is to "conduct studies that are reproducible, comparable and verifiable, compared to existing alternative approaches", which is one of the main objectives of the LCA carried out in this deliverable. For this reason, all the impact categories recommended by the PEF methodology were initially selected for this analysis. However, it should be noted that given the difficulty of interpreting and communicating the results when many impact categories are analysed and given that the standard states that the categories can also be selected based on scientific publications results, only the most significant impact categories for the NEMMO project technologies were selected to be discussed in detail.

TABLE 2. IMPACT CATEGORIES RECOMMENDED BY THE PEF GUIDE

Impact Category	Units	Characterization method
***Climate change**	kg CO_2 eq	IPCC
Ozone depletion	kg CFC11 eq	EDIP
Ionising radiation	kBq U-235 eq	Human Health Effect
Photochemical ozone formation	kg NMVOC eq	LOTOS-EUROS
Particulate matter	disease inc.	PM Model
Human toxicity, non-cancer	CTUh	USEtox
Human toxicity, cancer	CTUh	USEtox
Acidification	mol H^+ eq	Accumulated Exceedance
Eutrophication, freshwater	kg P eq	EUTREND
Eutrophication, marine	kg N eq	EUTREND
Eutrophication, terrestrial	mol N eq	EUTREND
***Ecotoxicity, freshwater**	CTUe	USEtox
***Land use**	Dimensionless (Pt)	Soil Organic Matter
***Water use**	m^3 depriv.	AWARE
Resource use, fossils	MJ	CML 2002
Resource use, minerals and metals	kg Sb eq	CML 2002
Climate change - Fossil	kg CO_2 eq	IPCC
Climate change - Biogenic	kg CO_2 eq	IPCC
Climate change - Land use and LU change	kg CO_2 eq	IPCC

Four of these indicators have been highlighted in this LCA because they are considered as the most relevant indicators for this project, and they have been analysed with more detail along this deliverable. Besides, these indicators were also analysed in detail by Walker and Thies in their study on the environmental impact of stream turbine blades [6]. These indicators are:

- **Climate Change**: It is a major global problem nowadays, and reducing this impact is one of the main achievements that are expected out of this project. It is measured in kg of CO_2 equivalent referred to the functional unit of this analysis.
- **Freshwater ecotoxicity:** Environmental toxicity is measured as three separate impact categories which examine freshwater, marine and land. The emission of some substances, such as heavy metals, can have impacts on the ecosystem. Assessment of toxicity has been based on maximum tolerable concentrations in water for ecosystems.
- **Water use:** Water consumption is the use of water in such a way that water is evaporated, incorporated into products, transferred to other watersheds, or disposed into the sea. Water that has been consumed is, thus, not available anymore in the watershed of origin for humans nor for ecosystems.
- **Land use**. This indicator refers to the transformation from one land use type into another, which takes place in a unique land cover, possibly incurring changes in the carbon stock of that specific land, but not leading to a change in another system.

4.9. Software and databases

On the one hand, Simapro 9.2 was the software chosen to develop the LCA study [7]. Simapro is a flexible tool designed based on ISO 14040 and 14044. Besides, this software can simulate complex parametric models in different scenarios and calculate sensitivity analyses and statistical analyses.

On the other hand, the main databases chosen for this work were:

- **ECOINVENT database v3.7**: developed by ETH (Swiss Research Institute). It deals with energy generation, mineral resource extraction and basic industrial processes, waste treatment and transport [8].
- The **European reference Life Cycle Database** (ELCD) is a database established by the European Commission's Joint Research Centre (JRC) and integrated in the SimaPro LCA Software. The ELCD database contains data from industries such as the chemical and metal industry. It also includes data on energy production, transport, and end-of-life processes. The datasets are provided and approved by their respective industry associations.

4.10. Summary of the Goal and Scope definition

The following table summarises the goal and scope definition for the LCA of the NEMMO tidal farm system, describing the FU, system boundaries, scenarios and environmental impact categories that will be assessed.

TABLE 3. GOAL AND SCOPE DEFINITION OF THE LCA

Goal of the LCA	Environmental performance and benchmark.	To assess the environmental performance of the NEMMO blade system identifying main hotspots and provide a benchmark comparison with other tidal technologies.
System under study	Scenario 1: 34. 5 MW Magallanes tidal farm system in Wales. Scenario 2: A theoretical 100 MW Magallanes tidal farm.	
Functional Unit	1 kWh electricity produced with the Magallanes tidal system.	The LCA will determine the environmental impact per kWh electricity produced at the output of the tidal farm, within the two scenarios considered.
Scope	Cradle-to-gate approach (electricity)	The tidal energy conversion system has been analysed from manufacturing to final decommissioning after its service life, including recycling, re-use, and disposal. The impacts of the electricity generated have been analysed up to the point of connection to the grid.
System Boundaries	The following life cycle phases of the tidal farm will be considered within the boundaries of the study: Components Manufacturing, Trans-shipment, Installation, Operation and Final disposition (Figure 5).	System boundaries will include all elements of the tidal farm until the onshore connection point. Onshore substation, grid and distribution to consumer will be out with the scope.
Environmental Impact Categories	The LCA will focus on the following impact categories: Climate Change Freshwater Ecotoxicity Land Use Water Use	Impacts will follow the recommendations from the Product Environmental Footprint method [5]

5. Life cycle inventory analysis

Life Cycle Inventory preparation is the phase of the LCA that involves the collection of all values related to the inputs and outputs of material and energy flows throughout the entire life cycle of a product. To facilitate its understanding and to have a global vision of the components involved in the life cycle of a product, the inventory is usually broken down by studying each of the phases that make up the scope of the analysis.

Two types of data were considered in the Inventory: primary data, which was obtained from the first-hand information provided by the NEMMO project partners, and which refer to the processes in which the partners have direct involvement or control, and secondary data, relating to the upstream processes (extraction of raw materials) and downstream process (end of life) to the central phase of the analysis. The consideration of secondary data allows not losing the life cycle perspective and the information necessary for its consideration is normally taken from specialised databases such as the European Life Cycle Database version (ELCD) or Ecoinvent.

The information contained in the Life Cycle Inventory consists of concepts such as:

- Energy consumption (electricity, fuels, etc.).
- Consumption of auxiliary materials.
- Main components of floating system, mooring system and cable system.
- Useful lifespan of the main components.
- Dismantling actions.
- Waste management.
- Other relevant data.

In this study, most of the inventory data was provided by the project partners or estimated by TECNALIA and subsequently validated by the project partners. Particularly, Magallanes has provided primary data for the manufacturing, installation, operation and maintenance and end of life of the platform, mooring system and electricity transmission cable. Inpre has provided primary data related to the manufacturing and end of life of the blades

The characterization of the floating system, as well as the consumption and maintenance services needed during the lifetime of the platform was characterized by using data published of directly provided by Magallanes to carry out this LCA. The blades manufacturing process, which is one the main innovations addressed in NEMMO project, was characterised mainly using data from Inpre, which is the main manufacturer. Finally, estimations about the expected impacts of the improved floating systems if they were used in an optimized tidal energy farm were proposed by TECNALIA and validated by the project consortium. Besides, these hypotheses are in line with other assumptions considered to carry out the other deliverables of the NEMMO project.

6. Life cycle impact assessment. Results

Life cycle impact assessment aims to identify and assess the quantity and importance of environmental impacts. Impacts are calculated by stages to check which stages, raw material and flows generate the greatest environmental impacts and the reasons for these impacts. The assessment is carried out by applying a set of characterisation factors, which are defined by the calculation method used, to determine the environmental impacts generated through the quantification of indicators or impact categories. In this case, the indicators recommended by the European Comission in the PEF methodology were calculated. All these indicatos are collected in Table 2.

For the representation and discussion of the results obtained in the LCA, a more detailed initial assessment was made of each of the stages that form part of the life cycle of the tidal energy farms (construction of the blades, construction of the platform, construction of the farm, installation, operation, etc.). All these components are detailed in section 2. Subsequently, the impacts calculated in these sections were grouped together and the impacts associated with the life cycle of both tidal energy farm scenarios were calculated.

The results shown in this section are based on the information included in the life cycle inventory appendix (Appendix B).

6.1. Analysis of the components involved in the tidal energy farms (scenario 1)

This section analyses the core stage of the life cycle of the NEMMO tidal energy farm, which is the manufacture of its components, as well as the impacts caused during the operation phase. As mentioned in the scope of the study, firstly, a cradle-to-gate study was carried out to quantify all the impacts incurred in the construction and operation stages of the tidal energy farm and to identify in which stages the environmental impacts of the tidal energy farm have been mainly generated. For the quantification of the environmental impact, the main resources consumed in the construction stage of the energy tidal farm (e.g. construction of the blades and platforms), the auxiliary consumptions needed during the operation of the farm and the impacts derived from maintenance actions were identified. The main results obtained are detailed below.

6.1.1. Manufacture of a floating platform (1.5 MW)

The manufacture of the floating platform and all its components is, *a priori*, one of the stages with the greatest environmental impact due to the large amount of material used in each platform. In this sense, this section quantifies the environmental impact caused by the construction of each 1.5 MW platform through 16 environmental indicators.

To quantify the impact of each platform, the following components have been considered: vessel structure, PTO, rotor system and auxiliary systems (see Figure 2). The components included in each of these parts are detailed between Table 17 and Table 24 of the annex B “Life Cycle Inventory”.

As a summary, the impacts caused by the construction of each 1.5 MW-platform and by each of its components are shown in Table 4. **Looking into the global warming indicator, the total CO_2 emissions caused by the construction of one platform of 1,5 MW is 2349.8 tons, distributed amongst the vessel structure, PTO, rotor and auxiliary systems.**

Although in the LCA carried out in this deliverable all the indicators recommended by the European Commission in the PEF guide were calculated, the discussion of the results focused only on the four most representative indicators for the NEMMO project: climate change, ecotoxicity, land use and water use. In this sense, the relative distribution of each indicator that is caused by the different components of the platform is graphically represented in Figure 6

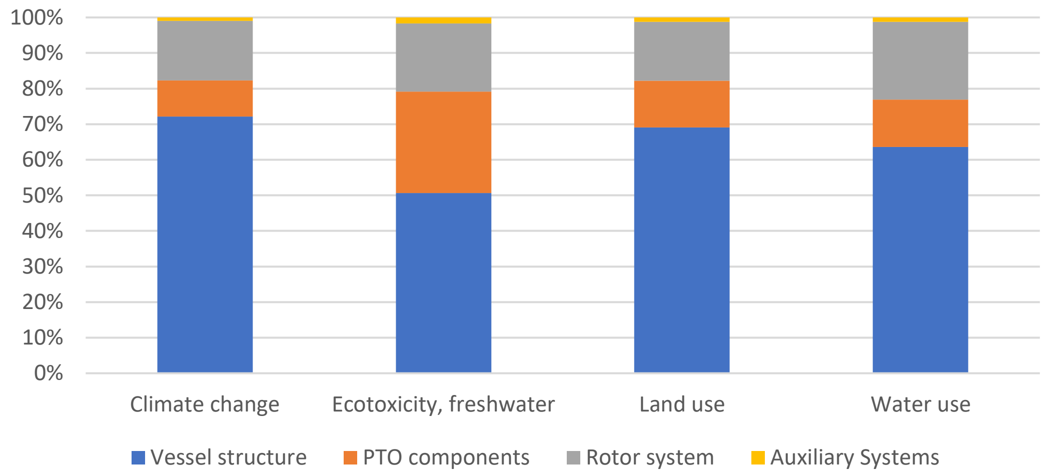

FIGURE 6. RELATIVE ENVIRONMENTAL IMPACT OF ONE PLATFORM OF 1.5 MW

TABLE 4. ENVIRONMENTAL IMPACT OF ONE PLATFORM OF 1.5 MW

Impact category	Units	Total	Vessel structure	PTO components	Rotor system	Auxiliary Systems
Climate change	kg CO_2 eq	**2.35E+06**	1.70E+06	2.38E+05	3.95E+05	2.16E+04
Ozone depletion	kg CFC11 eq	0.2	0.1	1.60E-02	2.70E-02	1.26E-03
Ionising radiation	kBq U-235 eq	1.91E+05	1.31E+05	1.85E+04	4.09E+04	1.48E+03
Photochemical ozone formation	kg NMVOC eq	10216.8	7279.4	1173.9	1672.2	91.2
Particulate matter	disease inc.	0.1	0.1	1.75E-02	2.26E-02	1.54E-03
Human toxicity, non-cancer	CTUh	0.1	3.00E-02	1.10E-02	8.64E-03	1.12E-03
Human toxicity, cancer	CTUh	1.13E-02	8.11E-03	1.41E-03	1.69E-03	6.30E-05
Acidification	mol H+ eq	12351.9	8760.3	1575.9	1868.2	147.5
Eutrophication, freshwater	kg P eq	1490.1	709.5	415.8	341.3	23.5
Eutrophication, marine	kg N eq	2955.4	2107.1	363.3	456.7	28.4
Eutrophication, terrestrial	mol N eq	2.97E+04	2.06E+04	4.25E+03	4.56E+03	3.18E+02
Ecotoxicity, freshwater	CTUe	1.24E+08	6.29E+07	3.54E+07	2.38E+07	2.09E+06
Land use	Pt	1.20E+07	8.32E+06	1.58E+06	2.00E+06	1.45E+05
Water use	m^3 depriv.	5.18E+05	3.30E+05	6.93E+04	1.13E+05	6.26E+03
Resource use, fossils	MJ	2.72E+07	1.90E+07	2.86E+06	5.11E+06	2.44E+05
Resource use, minerals and metals	kg Sb eq	60.6	15.6	31.6	10.3	3.1

Looking into the global warming indicator, the total CO_2 emissions caused by the different components of a platform are distributed as follows: vessel structure (72 %), rotor system (17 %), PTO components (10 %) and auxiliary systems (1 %). The reason for this is the huge amount of steel that is needed to build the structure of the vessel. 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. The main raw material involved in the production of primary steel is pig iron. Besides, a content of around 20 % of secondary raw material (iron scrap) is considered in the dataset developed by Ecoinvent to simulate low-allowed steel, which is the main material used to simulate the impact of the platform structure.

In absolute terms, the construction of each platform generates 2349.8 tonnes of CO_2eq, most of which are of fossil origin (> 98 %) (Figure 7).

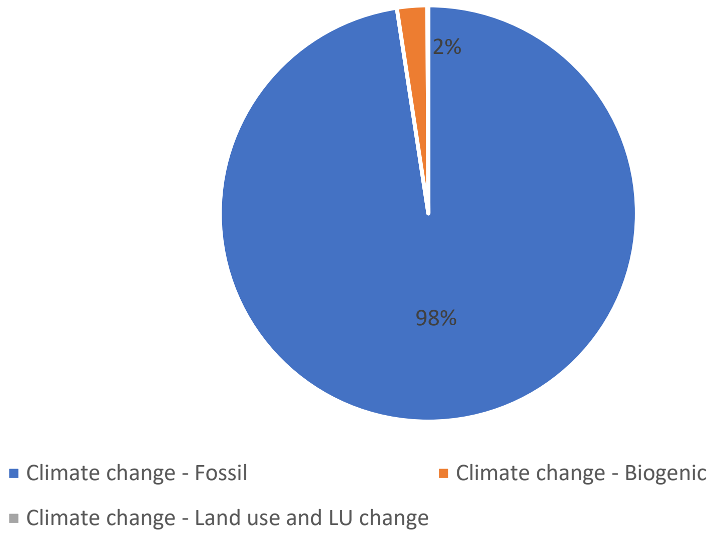

FIGURE 7. DISTRIBUTION OF GHG EMISSIONS CAUSED BY THE CONSTRUCTION OF A PLATFORM ACCORDING TO THEIR ORIGIN

As follows, each of the components of the platform are analysed individually. Regarding the remaining impact categories, the production of the steel needed to manufacture the **vessel structure** also represents the most significant impact in the other environmental indicators. Concretely, it generates the 51 % of the total freshwater ecotoxicity impact caused by the entire platform, and 69 % and 60 % of the total impacts measured with the indicators land use and water use respectively. The structure of the platform is composed of three main blocks: upper block, vertical block (or mast) and lower nacelle (or nacelle). This platform is completely made of steel, and its weight is 760 tonnes. On the other hand, in the category "structure of the platform", the 45 kg of the external metal enclosure of the ballast system, which is also made of steel, were considered. As both parts are made of steel, the impact caused by each of them is practically proportional to their weight in all the indicators analysed (10 % of the impact is caused by the ballast), as shown in Figure 8.

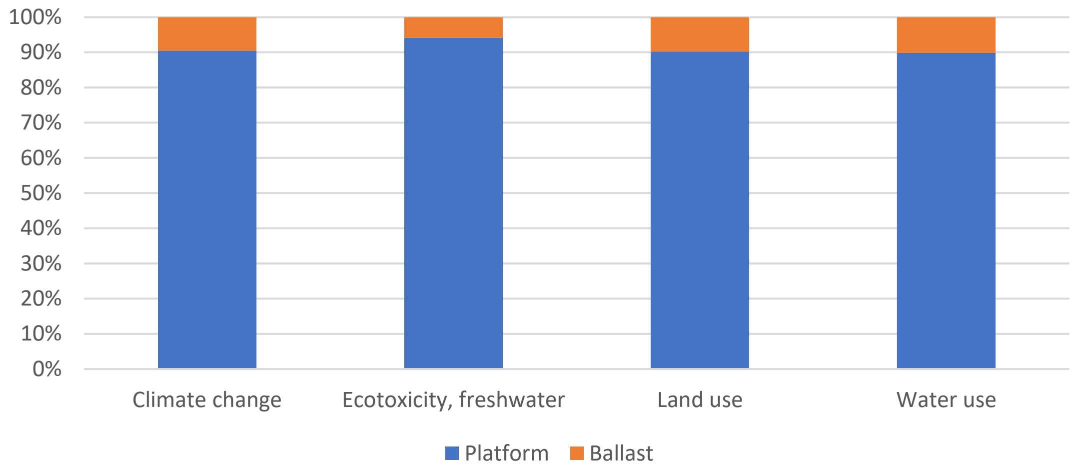

FIGURE 8. RELATIVE ENVIRONMENTAL IMPACT OF THE STRUCTURE OF THE PLATFORM

Regarding the impacts caused by the **PTO components**, the effect of this system on the freshwater ecotoxicity indicator is particularly significant, accounting for 28 % of the total impact of the platform. Looking at the other three indicators highlighted, the PTO system represents around 10-13 % of the total impact of the platform.

Within the components included in the PTO (Figure 9), the construction of the gearbox is the part that generates the highest impact on the indicators “climate change” (49 %), “land use” (38 %) and “water use” (33 %). On the other hand, the generator is the component of the PTO system with the greatest environmental impact on the freshwater ecotoxicity indicator (67 %).

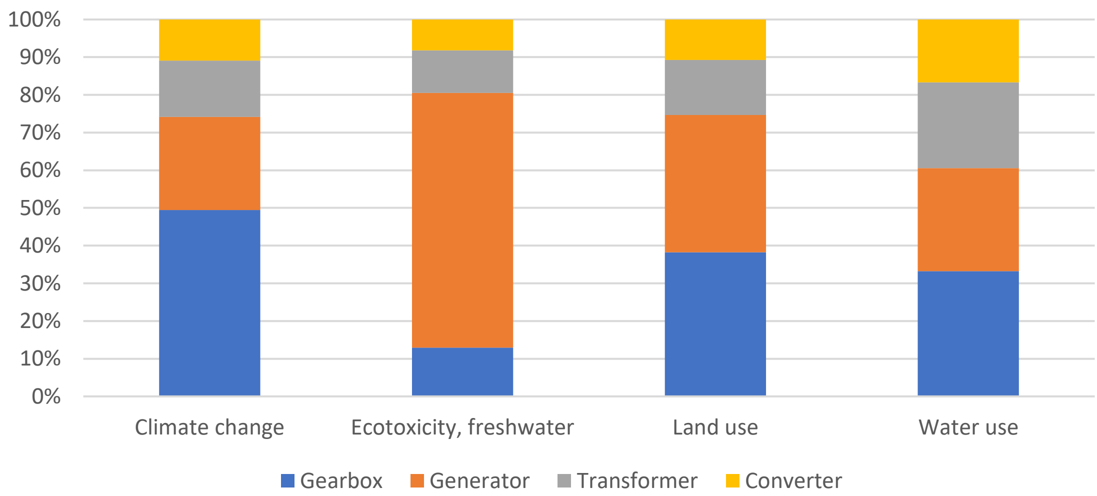

FIGURE 9. RELATIVE ENVIRONMENTAL IMPACT OF THE PTO SYSTEM (1.5 MW)

As for the **ancillary components**, their environmental impact is insignificant compared to the rest of the platform's components. In fact, their contribution is less than 2 % in all the indicators highlighted. Within the impact of each of the auxiliary systems, it is worth highlighting the impact generated by the fuel tank, which generates 46 % of the GHG emissions of all this equipment (Figure 10).

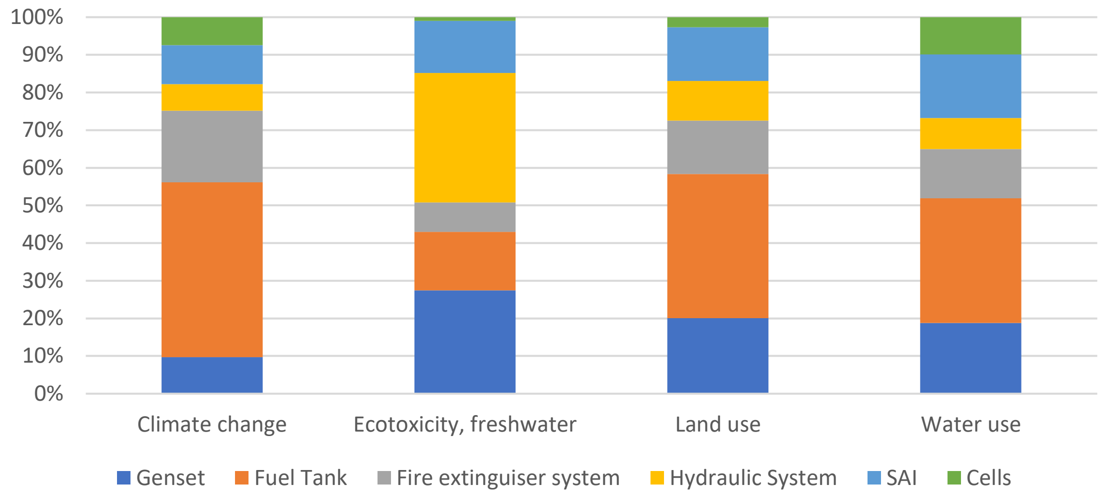

FIGURE 10. RELATIVE ENVIRONMENTAL IMPACT OF THE AUXILIARY SYSTEMS (1.5 MW)

Finally, with respect to the **rotor system**, the relative impact generated by this system, measured through the four indicators highlighted, is around 20 % of the total impact of the platform in all cases.

The rotor system consists of 4 main components, which are the blades, the variable pitch system, the main shaft, and the bearings. Of these, the variable pitch system is the one that generates the highest environmental burden in the four indicators highlighted in this study (Figure 11). In fact, its relative weight ranges from 55 % of the total impact in the "water use" indicator to almost 81 % in the "freshwater ecotoxicity" indicator.

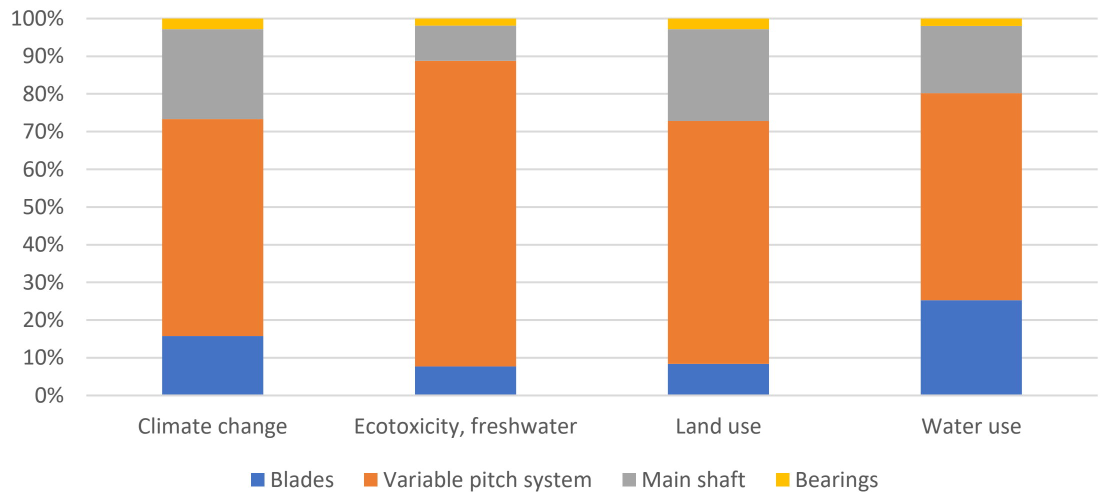

FIGURE 11. RELATIVE ENVIRONMENTAL IMPACT OF THE ROTOR SYSTEM (1.5 MW)

As one of the main aims of the NEMMO project is to develop improved blades, a more detailed analysis of the impacts caused in the blade manufacturing process has been carried out in this study. In this sense, the impacts caused by the manufacture of a blade are shown in Table 5, and the impacts related to the different concepts involved in the manufacture of a blade are shown in Figure 12.

TABLE 5. ABSOLUTE ENVIRONMENTAL IMPACTS OF THE MANUFACTURE OF A BLADE (1.5 MW)

	Climate change	Ecotoxicity, freshwater	Land use	Water use
Unit	*kg CO_2 eq*	*CTUe*	*Pt*	*m^3 depriv.*
Total	**10271.0**	**301790.1**	**27491.7**	**4738.5**
SM resin	5578.1	177808.9	13576.2	2675.1
Fibre glass reinforced polyester	3449.9	81638.4	8772.5	1578.5
Gel coat	126.6	5726.2	326.4	61.8
Adhesives	375.1	28384.4	762.5	309.8
Electricity	495.3	5384.2	1428.8	100.9
Waste flows	1.3	24.2	80.9	1.7
Transport	244.4	2823.6	2544.2	10.5

As a result, the production of each of the blades designed in the NEMMO project generates around 10.2 tonnes of CO_2eq. This value is in line with the results published by Walker and Thies in this publication [6]], where they compared the LCA results for different tidal stream turbine blades made of varied materials. Of these emissions, 54.3 % are caused by the SM resin production process, 33.6 % are produced in the glass fibre reinforced polyester production process and finally, the remaining 12 % of the emissions is addressed to the rest of the components (adhesives, gel coat, waste management, transport, electricity consumption in the blade manufacturing process, etc.). The use of SM resin and fibre glass as components of the blades are the main drivers of the impacts measured by the other environmental indicators as well. In the freshwater ecotoxicity indicator, they generate 59 % and 27 % respectively of the total environmental impact caused by the production of a blade. In the land use indicator, their contribution is 49 and 32 % and, in the water use indicator, they generate 56 and 33 % of the total impact of a blade respectively.

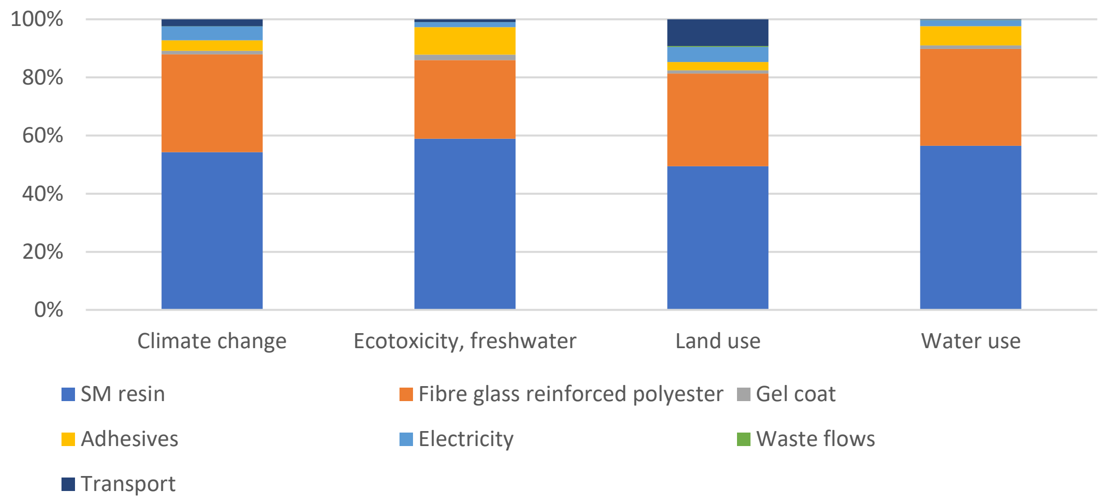

FIGURE 12. RELATIVE ENVIRONMENTAL IMPACT OF ONE BLADE (1.5 MW)

6.1.2. Manufacture of the mooring system

The general purpose of mooring system is to keep the platform in reasonable proximity of some target location and prevent it from being swept away by the sea current. According to the information provided by Magallanes, each platform requires four anchor lines made from steel and with a total weight of 760 tonnes.

Taking into account the impact of producing each kg of steel, as well as the impacts of processing the metal to manufacture the final products, the environmental impacts caused by the mooring system of each platform are collected in Table 6. Looking into the global warming indicator, the total CO_2 emissions caused by the mooring system is 1620 tonnes.

TABLE 6. ABSOLUTE ENVIRONMENTAL IMPACTS OF THE MOORING SYSETM OF ONE PLATFORM

	Units	Value
Climate change	kg CO_2 eq	1.62E+06
Ecotoxicity, freshwater	CTUe	3.61E+07
Land use	Pt	9.88E+06
Water use	m^3 depriv.	5.52E+05

6.1.3. Manufacture of the electricity transmission cable

The last of the components considered in the tidal energy farms is the power transmission cable that connects the platform to the onshore substation.

As detailed in the life cycle inventory section (appendix B), the use of two types of cables was considered: a 132 kV cable connecting the entire tidal energy farm to the onshore substation, and 33 kV cables to establish the connection between each of the platforms. The composition of each cable is collected in Table 21.

From an environmental point of view, the impacts of producing one meter of each type of cable are collected in Table 7. The 132 kV cable has a significantly higher impact than the 33 kV cable. The main reason for this fact is that the former has been considered to have a weight per metre of 89 kg, while the latter has a weight per metre of 29 kg/m. The materials that make up each of these cables are detailed in Appendix B of this report. Depending on the number of platforms installed in each tidal energy farm, the metres of cable required vary. For the case studies analysed in this report, the metres of cable used for each scenario are collected in the life cycle inventory.

TABLE 7. ABSOLUTE ENVIRONMENTAL IMPACTS OF PRODUCING ONE METER OF EACH TYPE OF CABLE

	Unit	132 kV subsea cable. 1m of cable	33 kV subsea cable. 1m of cable
Climate change	kg CO_2 eq	307.2	96.6
Ecotoxicity, freshwater	CTUe	223244.4	64851.9
Land use	Pt	4203.8	1277.7
Water use	m^3 depriv.	132.8	40.2

6.2. Analysis of the 34 MW tidal farm made up of 23 – 1.5 MW platforms (scenario 1)

Within the exploitation phase of the tidal farms, the first scenario addressed in this study contemplates the analysis of a tidal energy farm consisting of 23 platforms of 1.5 MW each. The lifespan of the farm is 25 years, and the expected energy to be generated each year, considering its capacity factor, is 94363 MWh.

To determine the environmental impacts caused by the tidal farm during its 25 years of operation, it was taken into account, in addition to the impacts caused by the manufacture of the platforms and the rest of the tidal energy farm components, the preventive maintenance actions of the farm, the impact of the components that need to be periodically replaced, and the impacts that the tidal farm will cause at the end of its useful life, following the most common dismantling scenarios for each type of material (End-of-Life impacts).

In this sense, the impacts generated by each MWh produced in the tidal farm, measured through all the indicators recommended by the European Commission in the PEF methodology, are shown in Table 8. On the other hand, the total impacts caused by the wind farm in the 25 years of its useful life, measured through the indicators highlighted in this LCA, as well as the breakdown between the components that generate each impact, are shown in

Table 9 in absolute values and in Figure 13 in percentage values. As can be seen in this table, most of the impacts are generated due to the infrastructure of the core module (CM.I). Only some minor impacts are caused by the consumption of the materials considered in the upstream module (UM).

TABLE 8. ABSOLUTE ENVIRONMENTAL IMPACTS, PER KWH PRODUCED IN THE 34 MW TIDAL ENERGY FARM

Impact Category	Units	Value (per kWh)
Climate change	g CO_2 eq	40.40
Ozone depletion	kg CFC11 eq	3.01E-03
Ionising radiation	kBq U-235 eq	5675.10
Photochemical ozone formation	kg NMVOC eq	154.52
Particulate matter	disease inc.	2.34E-03
Human toxicity, non-cancer	CTUh	9.42E-04
Human toxicity, cancer	CTUh	3.66E-04
Acidification	mol H+ eq	204.38
Eutrophication, freshwater	kg P eq	28.91
Eutrophication, marine	kg N eq	48.76
Eutrophication, terrestrial	mol N eq	475.01
Ecotoxicity, freshwater	CTUe	2.06E+06
Land use	Pt	2.29E+05
Water use	m^3 depriv.	1.10E+04
Resource use, fossils	MJ	5.19E+05
Resource use, minerals and metals	kg Sb eq	1.09

TABLE 9. ABSOLUTE ENVIRONMENTAL IMPACTS OF THE 34 MW TIDAL ENERGY FARM IN ITS ENTIRE LIFETIME

	Climate change	Ecotoxicity, freshwater	Land use	Water use
Unit	*kg CO_2 eq*	*CTUe*	*Pt*	*m^3 depriv.*
Total	**9.36E+07**	**4.72E+09**	**5.29E+08**	**2.55E+07**
CM.I. Platform	5.40E+07	2.85E+09	2.77E+08	1.19E+07
CM. I. Mooring system	3.72E+07	8.29E+08	2.27E+08	1.27E+07
CM.I. Electrical connections	1.41E+06	1.01E+09	1.91E+07	6.04E+05
CM.I. Replacements	8.02E+04	6.27E+06	5.37E+05	2.20E+04
CM.I. Corrective maintenance	9.84E+04	1.84E+06	5.84E+05	9.16E+03
UM. Upstream	7.15E+05	2.26E+07	3.92E+06	3.03E+05
CM.I. EoL recycling (per platform)	1.45E+03	2.55E+04	8.53E+04	1.82E+03
CM.I. EoL recycling (per platform)	4.19E+03	2.94E+06	1.25E+05	1.34E+03

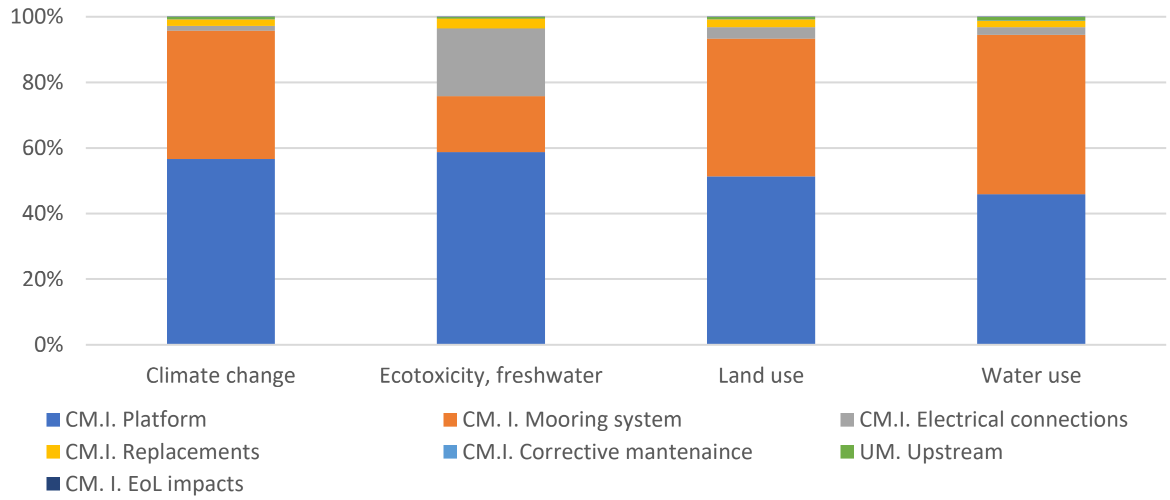

FIGURE 13. RELATIVE ENVIRONMENTAL IMPACT PER KWH OF ELECTRICITY PRODUCED IN THE 34 MW TIDAL ENERGY FARM

As a result of this analysis, the production of each kWh of electricity generates, among other environmental impacts, 40.40 g of CO_2eq in the 34 MW tidal farm. Looking at the relative distribution of the impacts depicted in Figure 13, most of the highlighted impacts are generated by the manufacturing of the tidal farm's equipment. Of all the components, the impact associated with the manufacture of the platform is the largest contributor to the impact measured by three of the four environmental indicators, accounting for 58 % of the GHG emissions, and 61 % and 53 % of the total impacts measured by the freshwater ecotoxicity and land use indicators, respectively. On the other hand, the impact caused by the mooring system is significant. This system generates 40 % of the total GHG emissions associated with the production of each kWh and is the main source of the impact measured by the indicator "water use" (50 %).

From the above analysis it can be concluded that the construction of the tidal energy farm components is the main cause of the environmental impacts allocated to each kWh of electricity generated. Therefore, it is important to optimise the design of this equipment as much as possible.

Some of the possible strategies that could reduce the environmental impacts of the NEMMO tidal farm per kWh generated include:

- Increasing the useful lifetime of the equipment.
- Total or partial reuse of equipment.
- Reducing the weight of equipment (eco-design).
- Increasing the efficiency of electricity production (either by seeking locations with high potential for tidal energy generation or by increasing the efficiency of equipment).
- Promoting the use of secondary raw materials and the recyclability of equipment.

6.3. Analysis of the 100 MW tidal farm made up of 30 – 3.3 MW platforms (scenario 2)

To estimate the environmental impacts that could be generated in a more optimised tidal energy farm, this report includes the analysis of a hypothetical scenario of a tidal energy farm composed of 30 turbines of 3.3 MW and a total power of 100 MW.

The description of this farm, the resource consumptions and the varied materials that compose it can be found in Appendix B of this deliverable, which contains the life cycle inventory. Most of the data estimated for the characterisation of this hypothetical tidal energy farm was extrapolated from the data available for the farm defined in scenario 1.

In this study, it was considered that the farm with 30 3.3 MW-platforms will produce 273602 MWh of electricity per year. Taking into account that the useful lifetime of the tidal energy farm is 25 years, it will produce a total of 6840050 MWh during this period.

For the calculation, on the one hand, the total impact of the tidal energy farm was estimated using the information available in the life cycle inventory. As a conclusion, the impact of the farm is mainly generated due to the production of the materials necessary to manufacture the structure of the platform, as well as the mooring system and the transmission cable.

On the other hand, the total impact of the farm was divided by the MWh of electricity produced in 25 years to obtain the impacts per MWh produced. The impacts obtained are shown in Table 10. Graphically, the contribution of the main sources of impact has been represented in Figure 14, taking into account the four indicators highlighted throughout this report.

TABLE 10. ABSOLUTE ENVIRONMENTAL IMPACTS, PER KWH PRODUCED, IN THE 100 MW TIDAL ENERGY FARM

Impact Category	Units	Value (per kWh)
Climate change	g CO^2 eq	22.41
Ozone depletion	kg CFC11 eq	1.64E-03
Ionising radiation	kBq U-235 eq	2935.3
Photochemical ozone formation	kg NMVOC eq	91.1
Particulate matter	disease inc.	1.35E-03
Human toxicity, non-cancer	CTUh	6.34E-04
Human toxicity, cancer	CTUh	1.85E-04
Acidification	mol H+ eq	119.3
Eutrophication, freshwater	kg P eq	20.4
Eutrophication, marine	kg N eq	28.3
Eutrophication, terrestrial	mol N eq	286.4
Ecotoxicity, freshwater	CTUe	1.52E+06
Land use	Pt	1.30E+05
Water use	m^3 depriv.	6231.3
Resource use, fossils	MJ	2.87E+05
Resource use, minerals and metals	kg Sb eq	0.9

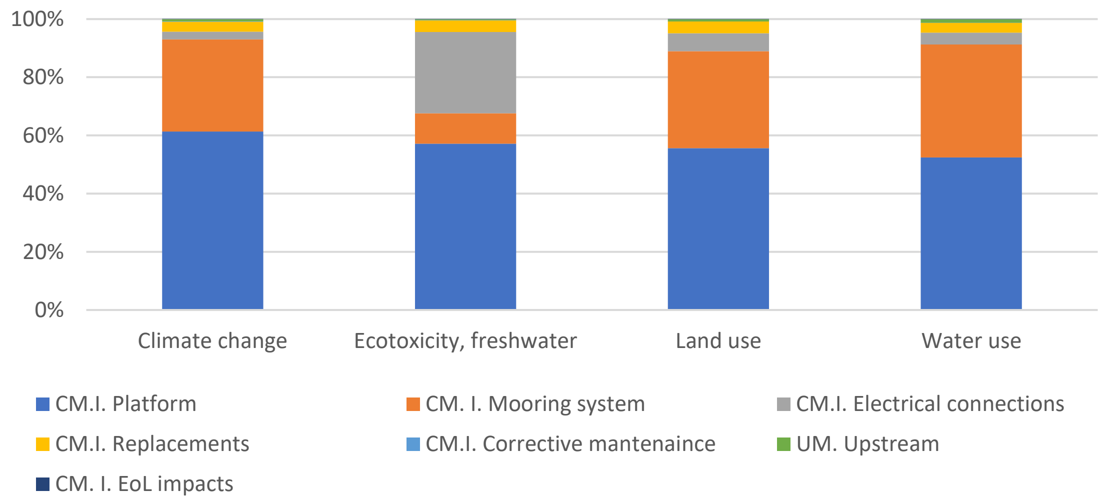

FIGURE 14. RELATIVE ENVIRONMENTAL IMPACT, PER KWH OF ELECTRICITY PRODUCED, IN THE 100 MW TIDAL ENERGY FARM

In this scenario, 22.41 kg CO_2eq are generated for every MWh of electricity produced in the tidal energy farm. Looking at Figure 14, the fact that more than half of the environmental impact measured by the four indicators is caused by the steel of the platform structure, can be seen at first glance. Also noteworthy is the impact caused by the steel forming the mooring system, which generates between

30-40 % of the total impact as measured by the indicators climate change, land use and water use. Finally, the transmission cable connecting the platforms to the onshore substation has a significant impact on the ecotoxicity indicator.

If this indicator is analysed in more detail through a network diagram (Figure 15), it can be seen that the impact of the cable is mainly caused by its copper content. On the other hand, within the platform components, the impact caused by the PTO system is very significant, representing up to 22.5 % of the total impact.

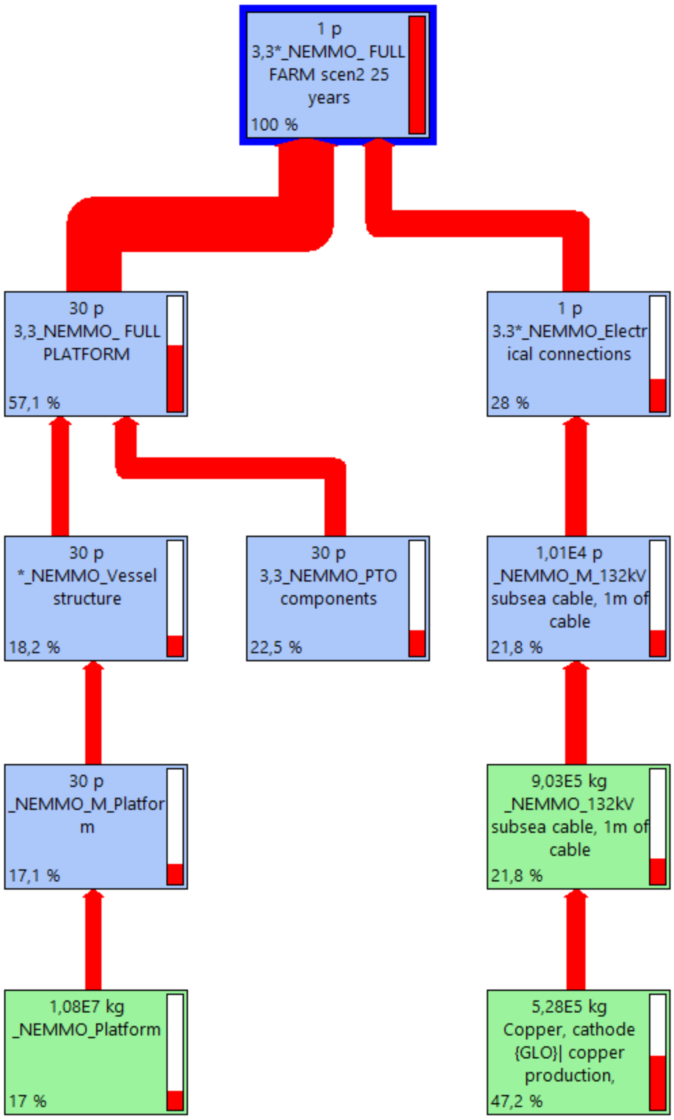

FIGURE 15. NETWORK DIAGRAM OF THE FRESWATER ECOTOXICITY. F.U 1 KWH ELECTRICITY GENERATED. SCENARIO 2

6.4. Comparison of results from both scenarios

If we compare the results obtained in the second scenario with the results obtained for the first scenario (Figure 16), we observe that the assumed optimisation of the tidal energy farm capacity and the increase in turbine power considerably reduces the environmental impact per MWh generated. In the case of the climate change indicator, GHG emissions from the second scenario farm have been reduced by 44.5 % compared to the first scenario farm (from 40.40 kg CO_2eq to 22.41 kg CO_2eq). This reduction is similar to that obtained for the indicators " land use” and “water use”, which are 43.2 % and 43.5 % respectively. Finally, in the case of the "freshwater ecotoxicity" indicator, the difference between the two scenarios is minor. The reason is that this impact is largely due to the impact of the manufacturing of the transmission cable as well as the manufacturing of the PTO system, while almost all the impacts measured with the other environmental indicators are due to the steel used in the platform and the mooring system. As the size and weight of both the cable and PTO components have increased with increasing turbine power, the reduction in this indicator is smaller. In addition, it has been considered that there are no differences in the platform structure and the mooring system of each platform in both scenarios.

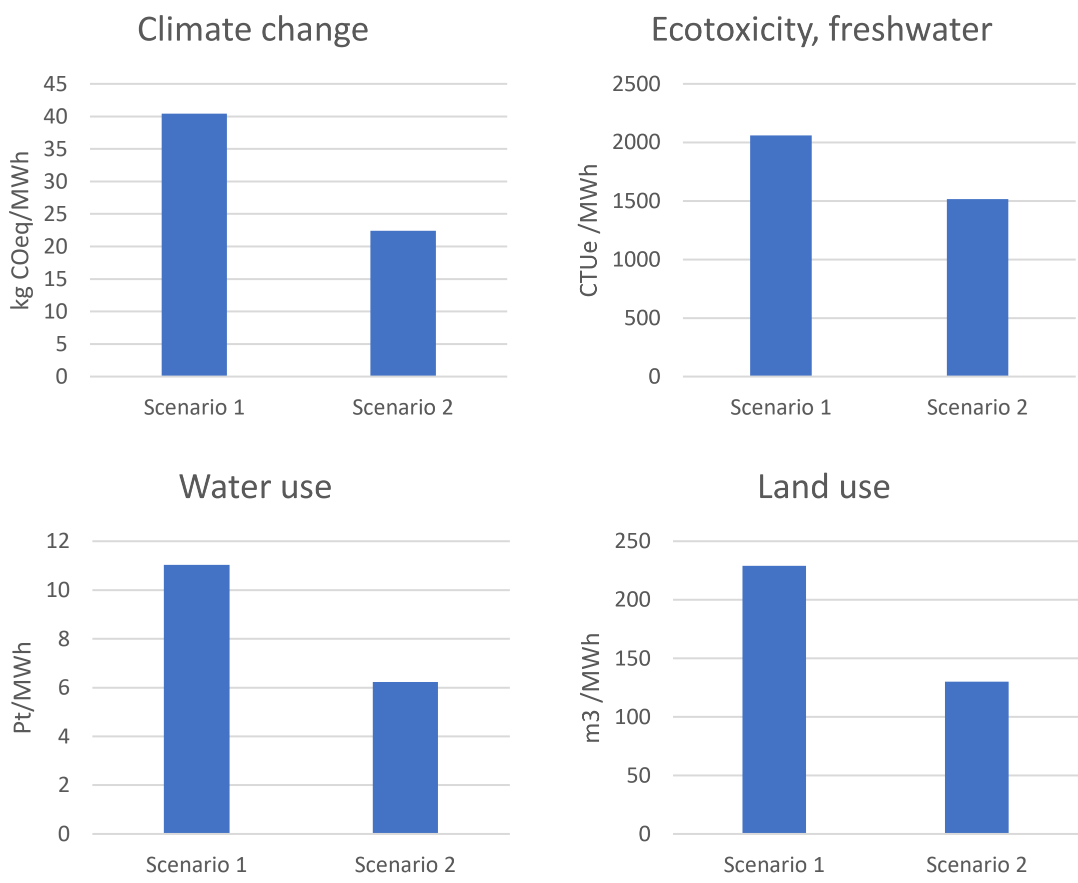

FIGURE 16. COMPARISON OF IMPACTS OF BOTH SCENARIOS, PER MWH

6.5. Comparison of the impacts with other tidal energy systems

The review of other studies of tidal energy farms in the scientific literature shows that the design of ocean energy devices varies considerably, and their weight ranges from 190 to 1270 t depending on device type. Applying a life cycle perspective, environmental impacts of the tidal farms are linked to material inputs and are caused mainly by mooring, foundations and structural components, while impacts from assembly, installation and use are negligible for all device types [9].

Furthermore, another important conclusion drawn from the literature review is that, in the case of marine energy systems, the manufacturing and installation of the systems have a significant environmental impact from a life cycle perspective. However, in the case of other energy systems using fossil-based feedstocks, most of the environmental impacts are generated mainly in the operation phase of the plant [10], [11].

The GHG emissions (per kWh of electricity generated) for different tidal power generation systems are listed in Table 11. The total greenhouse gas emissions from ocean energy devices range from about 15 (Seagen turbine in the north of Scotland) to 37 (HS1000 in Scotland) g CO_2-eq/kWh.

Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis the same functional unit needs to be applied. Additionally, the scope of the assessments should be in-line: lifetime, approach, impact assessment method used, etc. Therefore, for comparative purposes, the result of the Climate Change impact category indicator has also been calculated using the Recipe MidPoint environmental assessment method, which is the main one used in the references marked in bold in Table 11. Applying this method to Scenario 2 of the NEMMO system, the results obtained are very similar to the ones obtained originally with the IPPC characterization method (22.19 g CO_2/kWh with Recipe MidPoint environmental assessment method *vs* 22.4 g CO_2eq/kWh with the IPPC characterization method) and can now be compared with those results in Table 11.

If we compare the results in Table 11 with those obtained throughout this report, it can be seen that the GHG emissions obtained in Scenario 1 (i.e. 40.40 g CO_2/kWh), are generally higher than the emissions found in the literature However, the system analysed in the first scenario is not fully optimised, as it is the scenario tested after incorporating the innovations carried out in the NEMMO project.

If the literature values are compared with the results from Scenario 2 (i.e. 22.4 g CO_2eq/kWh)., in which an optimised system is analysed, the obtained results are generally in line with those reported in literature and in the table

TABLE 11. TIDAL ENERGY DEVICES EVALUATED IN LCA STUDIES

Device Name (Developer)	Geog. 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		[9]
Minesto Deep Green 500	**Wales**	**Cradle-to-grave**	**0.5**	**25**	**26.3**	**Recipe 2010**	**[10]**
Seagen Turbine (Marine Current Turbines Ltd.)	Northern Ireland	Cradle-to-grave	1.2	20	15	Other	[12]
SeaGen Turbine (Marine Current Turbines Ltd.)	**Northern Ireland**	**Cradle-to-grave**	**1.2**	**25**	**25.5**	**ReCiPe 2008**	**[13]**
HydraTidal	**Norway**	**Cradle-to-grave**	**1.5**	**25**	**20.1**	**ReCiPe 2008**	**[13]**
HS100	**Scotland**	**Cradle-to-grave**			**37**	**ReCiPe 2008**	**[13]**
DeepGen Tidal Generation Ltd. (TGL). It is a tri-blade single turbine device.	UK	Cradle-to-grave		25	34.2	Other	[14]
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	[14]
ScotRenewables. It is a floating twin horizontal axis turbine device (SR200)	UK	Cradle-to-grave		20	23.8	Other	[14]
Flumill. This device is an original twin Archimedes' screw design.	UK	Cradle-to-grave		20	18.5	Other	[14]
Crest Energy (theoretical scheme)	New Zealand			100	1.8	Other	[15]

The differences in these comparisons can be manifold and therefore should always be handled carefully, these could include:

- Differences in the technologies and materials composition;
- Different databases or versions of a same data base (e.g. Ecoinvent v2.2 *vs* 3.7) used for the modelling of background processes and models applied to calculate them;
- Different energy mixes used;
- Different ways of modelling EoL, which can make the comparison between technologies complicated. [10] and [13], for example, 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 NEMMO, 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 (see section 3.6 on allocation criteria). These differences in modelling could also imply the difference in the results obtained.

Despite these differences, however, it can generally be concluded that the results obtained for Scenario 2 in NEMMO are very much in line with those obtained from Minesto Deep Green 500, SeaGen Turbine (Marine Current Turbines Ltd.) and HydraTidal, with the two former showing higher emissions and the latter lower, as reported in [10] and [13].

6.6. Sensitivity analysis and discussion of results

Having calculated the main LCA results for the two NEMMO tidal power scenarios, it can be seen where most of the environmental burdens occur. Actually, the impact caused by two of the tidal energy farm components stand out above the rest: the manufacture of the platform structure and the manufacture of the mooring system.

For the LCA, the platform structure has been considered to weigh 360 tonnes, while the anchoring system required to fix each platform weighs around 760 tonnes. In both cases, a redesign of their main elements could reduce the amount of material needed for their manufacture and consequently reduce their environmental impact.

Another factor that has a direct impact on the results obtained in the LCA is the estimated useful lifespan of each element. In the study carried out in this report, it was considered that the useful lifetime of the tidal energy farms is 25 years. However, it is thought that the useful lifespan of both the platform structure and the mooring system could be even longer, as both systems may be used in other tidal farms once the useful life of the first one has ended.

In this sense, this study has analysed how the GHG emissions attributed to each kWh generated in the tidal farms would be reduced as the lifetime of the platform structure and mooring system increases. The results obtained are plotted in Figure 17.

With respect to the emissions associated with scenario 1, if the lifetime of the platform were 50 years, GHG emissions per kWh would be reduced from 40.40 g CO_2eq/kWh to 32.14 g CO_2eq/kWh (-20.5 %). On the other hand, if the lifetime of the mooring system were increased from 25 to 50 years, the GHG emissions per kWh generated would decrease to 32.51 g CO_2eq/ kWh (-19.5 %). A third option would be to extend the lifetime of both components simultaneously. In that case, if both systems had a lifetime of 50 years, the emissions would be 24.25 CO_2eq/ kWh (-40.0 %).

In the case of the tidal power farm simulated in scenario 2, the GHG emissions per kWh would be reduced from 22.41 g CO_2eq/kWh to 18.69 g CO_2eq/kWh (-16.6 %) if the lifetime of the platform structure were 50 years instead of 25 years. On the other hand, if the mooring system had a lifetime of 50 years, the emissions per kWh would be 18.86 g CO_2eq/kWh (-15.8 %). Finally, if the lifetime of both steel components were 50 years, emissions would be reduced to 15.14 g CO_2eq/kWh (-32.4 %).

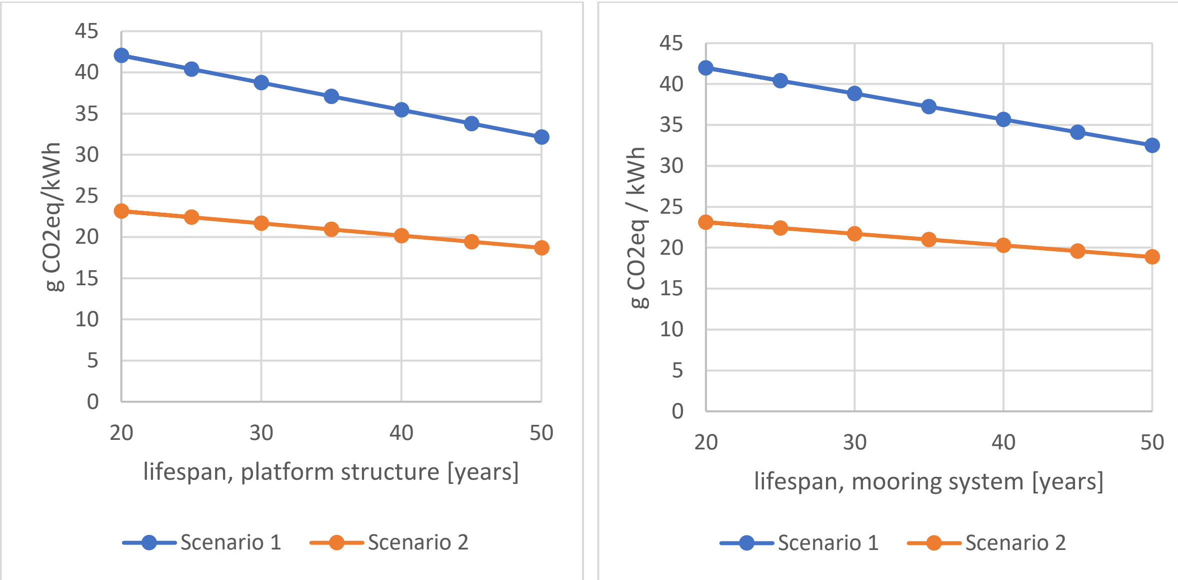

FIGURE 17. GHG EMISSION VARIATION VS DIFFERENT COMPONENT LIFETIMES

Besides, the Annual Energy Production (AEP) of each tidal energy farm is another key parameter that can significantly modify the impacts attributable to each kWh generated. Based on the study published by Neary et al. 2014 [16], which is the main reference used to calculate the AEP of these tidal farms, the energy production can significantly vary depending on the current speed, the rotor energy capture area, the operational availability, or the capacity factor, among others. Therefore, there are many factors whose optimisation can lead to an increase in the AEP. Any increase in the amount of electricity produced annually by the tidal energy farms will result in a proportional decrease in the environmental impacts per kWh produced and vice versa.

For example, based on estimates made by the NEMMO consortium, it is projected that the amount of electricity that could be generated in a specific location of Wales from each of the 1.5 MW platforms, taking into account the characteristics of the ocean currents, would be 2360 MWh. This represents a capacity factor of around 18 %, which is significantly lower than the factor simulated in this study using data from platforms located in Scotland (capacity factor: 31 %).

If we simulate the two tidal energy farms analysed in this study but taking into account this capacity factor, we obtain that the plant consisting of 23 1.5 MW platforms would produce 54280 MWh per year, while the plant consisting of 30 3.3 MW platforms would generate 157330 MWh per year. In this sense, the environmental impacts of these farms per KWh generated if they were located in Wales are shown in the Table 12.

TABLE 12. ABSOLUTE ENVIRONMENTAL IMPACTS, PER KWH PRODUCED, IN BOTH ENERGY FARMS (SECNARIO: WALES)

Impact Category	Units	Scenario 1 (23 platforms x 1.5 MW)	Scenario 2 (30 platforms x 3.3 MW)
Climate change	g CO^2 eq	70.26	38.97
Ozone depletion	kg CFC11 eq	5.23E-06	2.86E-06
Ionising radiation	kBq U-235 eq	9.87	5.10
Photochemical ozone formation	kg NMVOC eq	0.27	0.16
Particulate matter	disease inc.	4.07E-06	2.34E-06
Human toxicity, non-cancer	CTUh	1.64E-06	1.10E-06
Human toxicity, cancer	CTUh	6.36E-07	3.22E-07
Acidification	mol H+ eq	0.36	0.21
Eutrophication, freshwater	kg P eq	0.05	0.04
Eutrophication, marine	kg N eq	0.08	0.05
Eutrophication, terrestrial	mol N eq	0.83	0.50
Ecotoxicity, freshwater	CTUe	3582.10	2638.13
Land use	Pt	398.33	226.36
Water use	m^3 depriv.	19.18	10.84
Resource use, fossils	MJ	902.11	498.69
Resource use, minerals and metals	kg Sb eq	1.90E-03	1.64E-03

From the above table it can be seen that the location of the tidal energy farm is a critical factor in determining the amount of electricity generated and therefore, the associated environmental impacts. In fact, all impacts have increased by almost 74 % compared to the original analysis developed in this deliverable.

Finally, regarding the impacts associated with the blades manufacturing, whose design and construction has been optimised throughout the NEMMO project, they are conventionally manufactured from non-recyclable reinforced polymer composite materials. These materials have superior performance and resistance to ocean currents. However, most of the blades made from composite materials cannot be recycled with the current technologies and are disposed of in landfill or by incineration. As informed by Inpre, Innovative solutions are being tested at low TRL levels in which the composite materials of the blades are used as an additive to concrete after being crushed. These options are likely to acquire greater relevance in the near future as the ban to landfill increasingly comes into place.

Among the composite materials, the most common are those made of carbon fibres and especially, those made of glass fibres. Even though carbon fibre composite blades weight less than glass fibre, they cause more GHG emissions. Another alternative are blades made of steel. However, steel blades are around 2.5 times heavier, and it seems unlikely that steel will be a suitable material for large size blades [6].

For this reason, glass fibre reinforced polymer blades remain one of the most recommended options for turbines in tidal power farms. If we analyse the impacts caused in the life cycle of a blade (Figure 18), we can see that the impacts associated with the use of materials is a key factor and, therefore, any optimisation in the consumption of raw materials and a reduction in the waste generated will notably improve the environmental performance of the blades.

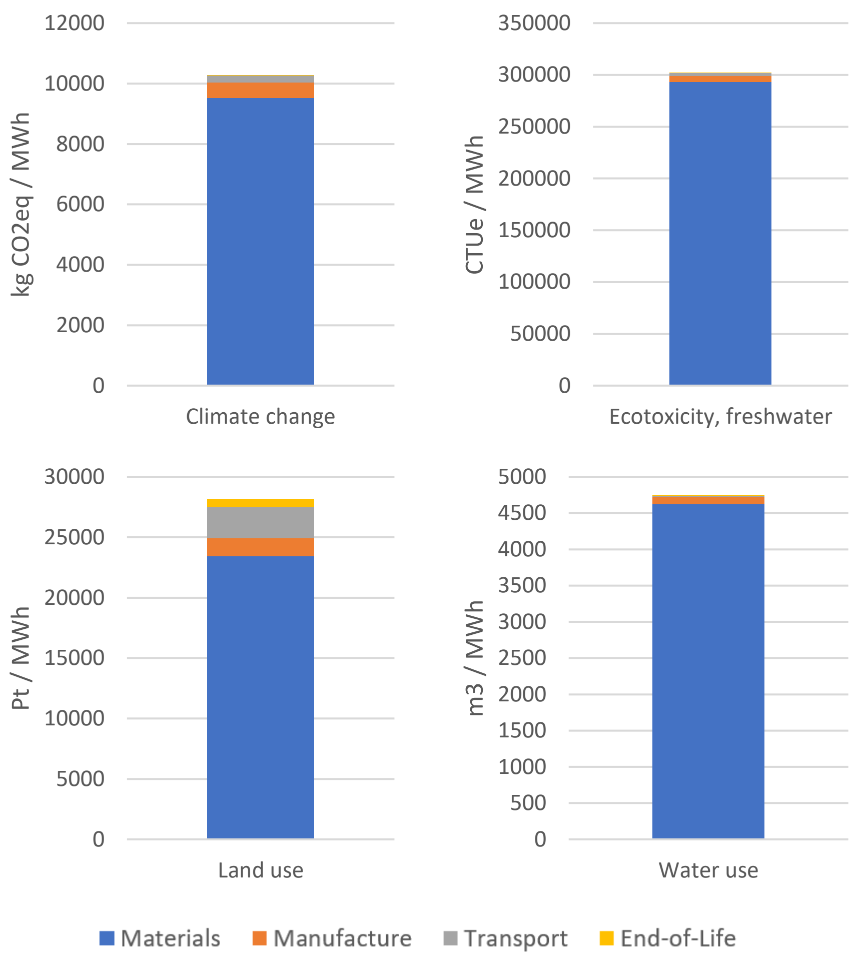

FIGURE 18. LIFE CYCLE IMPACTS OF A BLADE (NEMMO PROJECT)

One of the challenges faced by the NEMMO project was to design and manufacture more efficient and durable composite tidal turbine blades capable of operating in high-power turbines and, in that sense, the new blades have proven to have a longer lifetime than conventional blades and lower operating costs. The future challenge facing the industry now is to improve the recyclability of composite material blades at the end of their useful life, as this would significantly reduce the environmental impact of the electricity produced and increase the circularity of the materials.

7. Conclusions

The main objective of the NEMMO project is to create a larger, lighter, and more durable composite blade for floating tidal turbines, which will allow the devices to reach capacities of more than 2 MW.

The new blades developed in the project have been shown to have longer lifespan than conventional blades and lower operating costs. In this sense, and with the aim of continuing to identify the advantages associated with the new blades of the NEMMO project, the life cycle analysis methodology has been applied in this deliverable to calculate the environmental impacts of different tidal energy farms if the new blades be used.

The present deliverable contains the LCA of two tidal energy farms with the following characteristics:

- ✓ **Scenario 1**: A 34.5 MW installed capacity tidal energy farm, consisting of 23 platforms of 1.5 MW each.
- ✓ **Scenario 2**: A theoretical tidal energy farm of 100 MW of installed capacity composed of 30 platforms of 3.3 MW each.

The analysis has been done taking as a functional unit one kWh produced by the tidal energy farms, with a cradle-to-gate approach, and considering the recommendations given by the Product Category Rules document "electricity, steam and hot/cold water generation and distribution", developed in the framework of the International EPD® System.

The LCA study has been carried out considering the quantification of the environmental indicators proposed by the European Commission in the report "Recommendation on the use of Environmental Footprint methods" [5]. Among these indicators, four of them were selected to be analysed in detail throughout this study: climate change, freshwater ecotoxicity, water use and land use.

The main findings of this study are listed below:

- The results of the LCA conducted in this deliverable, measured through the quantification of the four indicators that have been selected as the most representative ones for this study, are shown in Table 13. In all cases, impacts are lower in scenario 2 than in scenario 1. The reason for this fact is that the system analysed in the first scenario is not fully optimised, as it is the scenario tested after incorporating the innovations carried out in the NEMMO project. However, scenario 2 represents a hypothetical tidal energy farm more optimized.

TABLE 13. RESULTS, PER KWH OF ELECTRICITY, IN BOTH SCENARIOS

	Units	Scenario 1	Scenario 2
Climate change	g CO_2 eq / kWh	40.40	22.41
Ecotoxicity, freshwater	CTUe / kWh	2059860	1517010
Land use	Pt / kWh	229050	130160
Water use	m^3 depriv. / kWh	11030	6230

- Of all the factors that determine the environmental impacts caused by each kWh of electricity generated in a tidal energy farm, the impact caused by the materials needed to build the structure of the floating platforms and the mooring systems are the most important (mainly steel). For example, in the tidal farm analysed in the first scenario, the impact associated with the manufacture of the platform accounts for 58 % of the GHG emissions, and 61 % and 53 % of the total impacts measured by the freshwater ecotoxicity and land use indicators. On the other hand, the manufacture of the mooring system generates 40 % of the total GHG emissions associated with the production of each kWh and is the main source of the impact measured by the indicator “water use” (50 %).

- The impacts caused in the life cycle of a blade used in a 0.75 MW-turbine are shown below. Most of the impacts are caused by the production of the materials used in the manufacture of the blades. For example, regarding climate change indicator, 92.7 % of the GHG emissions in the life cycle of a blade are generated by the materials used in its manufacture, 4.8 % is generated in the manufacturing process (mainly due to the electricity consumption), 2.4 % are generated by the transport and only 0.1 % are caused by the end-of-life treatment. A full description of all the materials and consumptions involved in the manufacturing process of the blades are described in section 9.2.1.

TABLE 14. LIFE CYCLE IMPACTS OF ONE BLADE

	Units	Value
Climate change	kg CO_2 eq	10282
Ecotoxicity, freshwater	CTUe	301987
Land use	Pt	28150
Water use	m^3 depriv.	4752

- One of the future challenges facing the tidal energy industry now is to improve the recyclability of composite material blades at the end of their useful life. This fact would significantly reduce the environmental impact of the electricity produced and increase the circularity of the materials. In addition, it would be advisable to eco-design the components that form part of tidal energy farms, especially the floating platforms and the mooring systems, in order to reduce the amount of material required and reduce the environmental impact of the farms without affecting their operability.

References

[1] C. Shetty and A. Priyam, "A review on tidal energy technologies," *Materials Today: Proceedings*, Jun. 2021, doi: 10.1016/j.matpr.2021.10.020.

[2] International Organization for Standardization, *UNE-EN ISO 14040:2006 - Environmental management- Life Cycle Assessment- principles and framework*. 2006.

[3] International Organization for Standardization, "ISO 14044:2006, Environmental management -- Life cycle assessment -- Requirements and guidelines," 2006.

[4] K. Lundmark and S. McGowan, "Electricity, steam and hot and cold water generation and distribution. Product Category Rules (PCR)," Stockholm, Sweden, 2021. [Online]. Available: http://www.environdec.com/PCR/Detail/?Pcr=5802

[5] Directorate-General for Environment, "Recommendation on the use of Environmental Footprint methods," 2021. https://environment.ec.europa.eu/publications/recommendation-use-environmental-footprint-methods_en (accessed Jul. 06, 2022).

[6] S. R. J. Walker and P. R. Thies, "A life cycle assessment comparison of materials for a tidal stream turbine blade," *Applied Energy*, vol. 309, Mar. 2022, doi: 10.1016/j.apenergy.2021.118353.

[7] "LCI databases in SimaPro." https://simapro.com/databases/

[8] "Ecoinvent." www.ecoinvent.org

[9] A. Uihlein, "Life cycle assessment of ocean energy technologies," *International Journal of Life Cycle Assessment*, vol. 21, no. 10, pp. 1425–1437, Oct. 2016, doi: 10.1007/s11367-016-1120-y.

[10] M. Kaddoura, J. Tivander, and S. Molander, "Life cycle assessment of electricity generation from an array of subsea tidal kite prototypes," *Energies (Basel)*, vol. 13, no. 2, 2020, doi: 10.3390/en13020456.

[11] M. G. Paredes, A. Padilla-Rivera, and L. P. Güereca, "Life cycle assessment of ocean energy technologies: A systematic review," *Journal of Marine Science and Engineering*, vol. 7, no. 9. MDPI AG, Sep. 01, 2019. doi: 10.3390/jmse7090322.

[12] C. A. Douglas, G. P. Harrison, and J. P. Chick, "Life cycle assessment of the Seagen marine current turbine," *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, vol. 222, no. 1, pp. 1–12, 2008, doi: 10.1243/14750902JEME94.

[13] M. Douziech, S. Hellweg, and F. Verones, "Are wave and tidal energy plants new green technologies?," *Environmental Science and Technology*, vol. 50, no. 14, pp. 7870–7878, Jul. 2016, doi: 10.1021/acs.est.6b00156.

[14] S. Walker, R. Howell, P. Hodgson, and A. Griffin, "Tidal energy machines: A comparative life cycle assessment study," *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, vol. 229, no. 2, pp. 124–140, 2015, doi: 10.1177/1475090213506184.

[15] B. M. Rule, Z. J. Worth, and C. A. Boyle, "Comparison of life cycle carbon dioxide emissions and embodied energy in four renewable electricity generation technologies in New Zealand,"

Environmental Science and Technology, vol. 43, no. 16, pp. 6406–6413, 2009, doi: 10.1021/es900125e.

[16] V. S. Neary *et al.*, "Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies," Albuquerque, New Mexico, 2014. [Online]. Available: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

8. Appendix A. Environmental Indicators. Definitions.

Climate Change: A phenomenon observed in temperature measurements that shows an average increase in the temperature of the Earth's atmosphere and oceans in recent decades. This indicator is also sometimes referred to as a "carbon footprint".

Ozone Depletion: Impact category that accounts for the degradation of stratospheric ozone due to emissions of ozone-depleting substances, for example long-lived chlorine and bromine containing gases (e.g., CFCs, HCFCs, Halons).

Ionising Radiation: This impact category accounts for the adverse health effects on human health caused by radioactive releases.

Photochemical Ozone Formation: Impact category that accounts for the formation of ozone at the ground level of the troposphere caused by photochemical oxidation of Volatile Organic Compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) and sunlight. High concentrations of ground-level tropospheric ozone damage vegetation, human respiratory tracts and manufactured materials through reaction with organic materials.

Particulate Matter: Impact category corresponding to harmful effects on human health due to emissions of particulate matter and its precursors (NOx, SOx, NH_3).

Human Toxicity – Cancer: Impact category that accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin as far as they are related to cancer.

Human Toxicity - Non-Cancer: Impact category that accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin as far as they are related to non-cancer effects that are not caused by particulate matter/respiratory inorganics or ionising radiation.

Acidification: Impact category that addresses impacts due to acidifying substances in the environment. Emissions of NOx, NH_3 and SOx lead to releases of hydrogen ions (H+) when the gases are mineralised. The protons contribute to the acidification of soils and water when they are released in areas where the buffering capacity is low, resulting in forest decline and lake acidification.

Eutrophication: Nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilised farmland accelerate the growth of algae and other vegetation in water. The degradation of organic material consumes oxygen resulting in oxygen deficiency and, in some cases, fish death. Eutrophication translates the quantity of substances emitted into a common measure expressed as the oxygen required for the degradation of dead biomass

Resource Use: Refers to the inventory of data collected to represent the inputs and outputs associated with each stage of the product supply chain being studied. The compilation of the Resource Use and Emissions Profile is completed when non-elementary (i.e. complex) flows are transformed into elementary flows.

Water Use: Water consumption is the use of water in such a way that water is evaporated, incorporated into products, transferred to other watersheds, or disposed into the sea. Water that has been consumed is, thus, not available anymore in the watershed of origin for humans nor for ecosystems.

Land Use: This indicator refers to the transformation from one land use type into another, which takes place in a unique land cover, possibly incurring changes in the carbon stock of that specific land, but not leading to a change in another system.

9. Appendix B. Life Cycle Inventory

This appendix contains the Life Cycle Inventory used to calculate the environmental indicators of the tidal energy farms throughout the report. Data is classified according to the life cycle phase to which they belong (upstream, core and downstream), as well as the stage or concept to which they refer. All the data included in this appendix has been provided directly by the project partners involved in the manufacturing and operation of the tidal energy farms or estimated by TECNALIA and subsequently validated by the project consortium to ensure that the data inventory is free of errors or inconsistencies.

9.1. Upstream module

The consumption of auxiliary substances necessary for the proper functioning of a tidal farm is shown below. On the one hand, Table 15 contains the annual consumptions of auxiliary substances for a tidal energy farm composed by 23 platforms of 1.5 MW. On the other hand, Table 16 contains the annual consumption of auxiliary substances for a wind farm with 30 platforms of 3.3 MW.

TABLE 15. CONSUMPTION OF AUXILIARY SUBSTANCES IN THE TIDAL ENERGY FARM WITH 1.5 MW TURBINES

	Value	Units
Lubrication oil consumption	11500	l/year
Antifouling paint consumption	4600	kg/year

TABLE 16. CONSUMPTION OF AUXILIARY SUBSTANCES IN THE TIDAL ENERGY FARM WITH 3.3 MW TURBINES

	Value	Units
Lubrication oil consumption	15000	l/year
Antifouling paint consumption	6000	kg/year

9.2. Core module (I): infraestructure

9.2.1. Tidal farm construction

The first of the stages that constitute the core module of the study is the analysis of the impacts caused as a consequence of the construction of the tidal energy farm, the necessary infrastructures and the decommissioning strategies at the end of its useful life. For the study, the tidal farm components within the assessment boundary comprise those components that are offshore, i.e., platforms, mooring lines and the electricity transmission cable up to the onshore connection point. Therefore, the onshore substation and the electricity transmission network will not be included within the system boundary under study.

The main equipment considered in this LCA is the floating system developed by Magallanes. It consists of a steel-built trimaran which incorporated a submerged part where the hydrogenerators are fitted. The 45-metre floating platform is suited with two 21-metre-hogh counter-rotating three-bladed rotors situated below the hull, which combined can produce up to 1.5 MW. As the platform floats, it does not involve any construction on the sea bottom and installation and decommissioning can be easily done.

The floating system is composed by four main components: vessel (platform), Power Take Off (PTO) system, rotor and auxiliary systems. Table 17 contains the main subcomponents of a 1.5 MW and 3.3 MW systems, as well as the main materials, weight and distance from supplier. The lifespan of the general installation is 25 years.

TABLE 17. MAIN COMPONENTS OF ONE FLOATING SYSTEM (1.5 AND 3.3 MW)

Component	Subcomponent	Main materials	Tonnes per platform (2 turbines) 1.5 MW	Tonnes per platform (2 turbines) 3.3 MW	Transport type	Distance from supplier (km)
Platform	Vessel structure	Steel	360	360	Sea transport	1400
	Ballast	Steel	45	45	Sea transport	1400
Power Take-Off (PTO)	Gearbox	Clean steel	27.9	61.38	Road transport	600
	Generator	Steel, copper, cast iron and aluminium	8.7	19.14	Road transport	1150
	Transformer	Aluminium, copper and steel	6	13.2	Road transport	1150
	Converter	Aluminium, copper and steel	4.4	9.68	Road transport	1150
	Brakes	Steel	0.1	0.22	Road transport	2230
Rotor	Blades	Fibreglass and resin, with an internal structural beam (blades are hollow filled with foam)	12	26.4	Road transport	736
	Variable Pitch system	Steel, fiberglass, cast iron, copper, and aluminium	58.16	127.95	Road transport	-
	Main shaft	Steel, cast iron	27	59.4	Road transport	-
	Bearings (chumaceras)	Steel	2.7	5.94	Road transport	-
	Oil tank	Steel	1	2.2	Road transport	20
Auxiliary System	Genset	Steel, copper, composite, aluminium	0.4	0.88	Road transport	1127
	Fuel Tank	Aluminium	1	2.2	Road transport	20
	Fire extinguisher system	Steel, composite	1	2.2	Road transport	-
	Hydraulic system	Steel, copper, aluminium, composite	0.2	0.44	Road transport	-

	SAI	Steel, lithium, copper, aluminium	0.45	0.99	Road transport	2225
	Cells	Steel, copper, aluminium	0.28	0.61	Road transport	1150

The lifespan of all components is 25 years, except for some auxiliary components, which must be periodically replaced. Components with a lifespan lower than 25 years are indicated in Table 18, as well as the number of times that they will be replaced in 25 years.

TABLE 18. COMPONENTS THAT ARE REPLACED DURING THE LIFETIME OF THE PLATFORM

Component	Lifespan [years]	Number of times it will be replaced in 25 years
Genset	4	6.25
Fuel Tank	10	2.5
Fire extinguisher system	2	12.5
SAI	6	4.1

In this LCA, a more detailed study of the manufacturing process of the blades has been carried out, as the optimisation of their manufacture and composition is one of the main objectives of the project. In this regard, the following information has been taken into account in relation to the new blades developed in the project. For 1.5 MW floating systems, the weight of each blade is 2.2 tonnes. There are three blades in each turbine, and each platform contains two turbines. In the end, the blades of a platform weight 13.2 tonnes. The components of each blade are collected in the following table. On the other hand, the weight of one blade in a 3.3 MW platform is 4.84 tonnes (29.0 tonnes per platform).

TABLE 19. COMPOSITION OF A BLADE

Material	Kg per blade (1.5 MW)	Kg per blade (3.3 MW)	Transport type	Distance from supplier (km)
Fibre glass reinforced polyester (56 %)	1200	2640	Maritime and road transport	3500
SM resin (standard) (vinyl ester resin) (39 %)	840	1848	Road transport	1050
Gel Coat (1 %)	25	55	Road transport	120
Adhesives (3 %)	66	145.2	Road transport	2700

The components of each NEMMO blade include fibre glass reinforced polyester (56%), resin (39%), gel coal (1%) and adhesives (3%). In principle, the original design plan for the blades was based on advanced composite material featuring nano-reinforced and antifouling bio-mimetic characteristics. The nano-reinforced resin was tested but disregarded as the infusion process in their manufacturing could not be completed (the nano-particles could not flow with the resin and impregnate the glass fiber). As for the anti-fouling, it has not been implemented in the blades either, but the project has undertaken a theoric analysis of its use.

In addition to the consumption of raw materials, it has been estimated that the construction of each blade in a 0.75 MW turbine requires an electricity consumption of 1200 kWh.

Regarding the residues generated in the manufacturing process of the blades developed in the project, Table 20 contains a summary of all the waste flows generated by each blade manufactured, as well as the end-of-life scenario for each of them.

TABLE 20. WASTE FLOWS PER MANUFACTURED BLADE

Material	Kg per blade (1.5 MW)	Kg per blade (3.3 MW)	Type of waste (hazardous/non-hazardous)	End of life treatment
Fibre glass reinforced polyester	210	462	Disposal - Non-Hazardous	landfill
SM resin (standard) (vinyl ester resin)	50	110	Disposal - Non-Hazardous once catalysed	landfill
Gel Coat	2	4.4	Disposal - Non-Hazardous once catalysed	landfill
Adhesives	0.0033	0.0072	Disposal - Non-Hazardous once catalysed	landfill

The vessel is anchored to the seabed with a 4-point mooring system. 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 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. In total, 92 anchor points will be required for a wind farm consisting of 23 platforms of 1.5 MW. The total weight of these chains will be 17562 tonnes. On the other hand, for a wind farm consisting of 30 platforms of 3.3 MW, 120 anchor points will be required, and the total weight of the mooring system will be 22860 tonnes.

Finally, the electricity transformed by the generator of each platform is transported onshore by an electricity transmission cable (umbilical cable). On the one hand, it has been estimated that each 1.5 MW platform is connected to the shored-based substation by 150 m of 33 kV cable, weighing 29 kg per metre. On the other hand, there is a 132 kV cable connecting the entire wind farm to the onshore substation. The weight of the 132 kV cable for a tidal energy farm constituted by 23 platforms of 1.5 MW is 311500 kg (89 kg/m).

Each of the two types of cables involved (33 kV and 132 kV) consists of a triple core of polymer-coated wires. The percentage distribution by weight of the materials that make up each of the two types of cables analysed is shown in Table 21.

TABLE 21. MASS COMPOSITION OF CABLES

Material	Composition (%) 33 kV cable	Composition (%) 132 kV cable
Steel	21.2 %	21.2 %
Copper	41.1 %	35.8 %
Lead	21.2 %	25.0 %
Polyethylene	27.1 %	25.2 %
Polypropylene	6.4 %	8.9 %

On the other hand, for the tidal energy park, consisting of 30 platforms of 3.3 MW, the required cable weights have been extrapolated taking into account the power increase of each platform and of the tidal farm as a whole.

9.2.2. Regular corrective maintenance actions

Tidal energy turbines periodically must undergo corrective maintenance tasks and some of their components need to be repaired and replaced. The corrective maintenance tasks carried out on tidal energy turbines are multiple and remarkably diverse, making it difficult to standardise and estimate the number of visits to be made per machine reliably. To carry out this analysis, it was considered that one corrective maintenance visit per platform per month is carried out. For each of the visits to the farm, it is assumed that the operators drive a total distance of 40 km (round trip).

TABLE 22. REGULAR CORRECTIVE MAINTENANCE ACTIONS

	Tidal farm with 23 platforms of 1.5 MW	Tidal farm with 30 platforms of 3.3 MW
Monthly visits to the tidal farm by the operators to carry out regular corrective maintenance tasks.	20	25

9.2.3. End-of-life stages of the tidal farm. Decommissioning.

The following assumptions were made for the end-of-life scenarios of the tidal energy farm components with the help of the NEMMO partners, and specially Magallanes. As mentioned in **section 3.6**, when modelling the end-of-life scenarios for NEMMO, the polluter pays principle (PPP) has been applied. This means that the full environmental impact of the generation of the waste until the gate of a waste processing plant (collection site) has been applied to the NEMMO system. On this basis, no credits (negative flows) have been applied as an output based on recycling rates when modelling EoL stages in NEMMO.

TABLE 23. MOST COMMON END-OF-LIFE SCENARIOS FOR PLATFORM COMPONENTS

Material	EoL scenario 33 kV cable	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

Core module (II). Operation of tidal energy farms

This phase comprises the entire period during which the tidal energy farms are in operation.

The final purpose of a tidal energy farms is the generation of electricity. Similar to other forms of renewable energy, the power produced by ocean energy technologies can vary significantly throughout the year or even within the range of a few days and is directly dependent on the available resource.

Based on the techno-economic analysis carried out within the NEMMO project activities (D6.3), the capacity factor, provided as a range, and the potential electricity output were established for both Scenarios of the NEMMO project (Table 24).

TABLE 24. CAPACITY FACTOR AND ELECTRICITY OUTPUT FOR BOTH SCENARIOS

Aspects to consider	Value (scenario 1): 23 platforms x 1.5 MW	Value (scenario 2): 30 platforms x 3.3 MW	Units
Capacity factor (%)	30-45	30-45	%
Expected average yearly produced electricity	94393	273602	MWh
Expected energy losses (due to equipment degradation)	4-4.5	4-4.5	%
Average lifetime of the tidal energy farm	25	25	years
Total energy generation (lifetime)	2359825	6840050	MWh