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FULL LIFE CYCLE ASSESSMENT OF A WAVE ENERGY CONVERTER

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Abstract

The Pelamis wave energy converter is emerging as one of the most promising devices to harness the available power in the waves. This study examines the environmental impacts of the device, presenting the results as a set of impact potentials, and demonstrating that it performs well in comparison to other renewable energy converters and fossil-fuelled generators.

1 Introduction

The continued drive to mitigate climate change by reducing Greenhouse Gas (GHG) emissions has led to an increase in demand for low-carbon energy sources. This has resulted in the development of new technologies to harness renewable energy. However, while the energy sources are themselves ‘carbon-free’, there are wider environmental impacts associated with the process of converting the energy into electrical power. In order to make informed decisions for future developments of the energy system, it is therefore necessary to develop a detailed understanding of the life cycle environmental impacts that arise indirectly from power generation due to the manufacture, operation and decommissioning of generators and network infrastructure.

In the United Kingdom (UK) the Government has introduced ambitious targets to decarbonise the electricity supply, with the latest carbon budget aiming to reduce average emissions from generation from current levels of around 500 gCO_2/kWh to around 50 gCO_2/kWh by 2030 [3]. It is expected that marine energy will be an important contributor, with resources believed to have the potential to supply around 20 per cent of electricity demand [5].

The Pelamis Wave Energy Converter (WEC) is emerging as one of the most promising devices to harness this available power. Developed by Pelamis Wave Power Ltd, the P1 version of this semi-submerged offshore device was successfully installed at the world’s first commercial wave farm at Aguaçadoura, off the coast of Portugal, in 2008. The experience gained has been fed directly into the development of the second-generation P2 device, currently on test at the European Marine Energy Centre. Several projects are currently in the development stages, with lease agreements having been agreed for two farms comprising around 70 devices off the coast of Scotland [13]. It is therefore important to understand the life cycle impacts of these devices. To date very few life cycle assessments have been carried out in this sector, and many of these concentrate only on carbon emissions and embodied energy.

In 2007 an in-depth life cycle carbon and energy audit was published by Parker *et al.* [12] on the Pelamis P1 device, based on detailed data from the manufacturer. This study found that the energy and carbon intensities were 293 kJ/kWh and 23 gCO_2/kWh respectively. The current paper builds upon the work carried out by Parker *et al.* by expanding the analysis to cover a broad range of environmental impacts. In particular this includes an expansion of the carbon analysis to include all GHG emissions. This will involve creating an inventory of all environmentally significant resource use and pollutant emissions at each stage of the device life cycle, from ‘cradle-to-grave’, and then characterising these according to their ‘impact potential’. This detailed study will allow better comparison with existing and future generating technologies.

2 Life Cycle Assessment

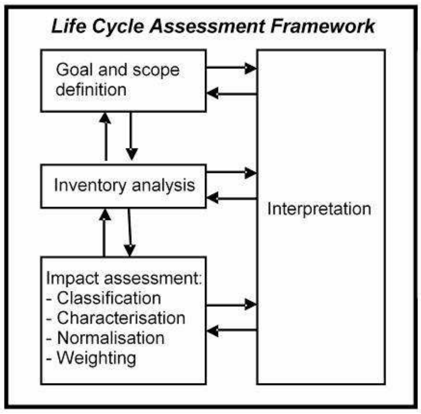

Figure 1: Life cycle assessment framework [4]

Life Cycle Assessment (LCA) is an established technique for identifying and evaluating the inputs, outputs and potential environmental impacts of products or services. The process is illustrated in Figure 1. It involves systematically analysing resource use and pollutant emissions at each stage of the product life cycle; from extraction of raw materials, through manufacture and operation to decommissioning and disposal. The detailed results are then described as a set of identifiable consequences or ‘impact potentials’. This mature methodology is governed by the ISO 14040 series of international standards [1], and has already been applied to a range of energy technologies and networks.

The results of this comprehensive analysis will highlight the components, materials or stages of the life cycle with the largest environmental impacts. This information can be used in design development and marketing product environmental credentials, and will also be valuable in planning the development of an environmentally-sustainable energy system. More information on LCA can be found in reference [4].

3 The Pelamis Wave Energy Converter

Figure 2: Pelamis wave energy converter [13]

The Pelamis is a semi-submerged snake-like offshore wave energy converter. The P1 version is 120 m long, 3.5 m in diameter and rated at 750 kW (Figure 2). It has four cylindrical sections linked by three power conversion modules at the hinged joints. The compliant moorings allow the Pelamis to face into the oncoming waves, and the joints flex vertically and horizontally (heave and sway) as the wave front passes. This motion is resisted by hydraulic rams housed within the power conversion modules. These rams pump high-pressure oil into banks of accumulators, which are drained at a constant rate through hydraulic motors, in turn driving induction generators. The resistance of the rams can be tuned to provide a resonant response in small sea states to maximise power capture, and can also assist in protecting the device from potentially damaging storm waves.

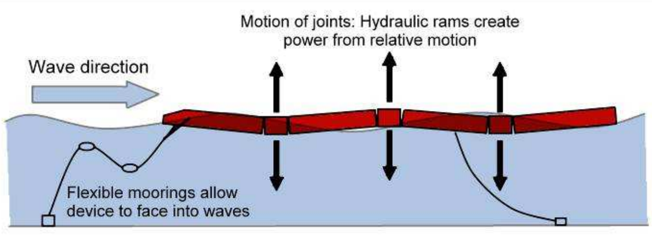

Figure 3: Side view of the Pelamis [12]

In order to enable comparison with the analysis published by Parker *et al.* in 2007 [12], many of the fundamental assumptions and base data have been kept the same in the current study. Therefore, in line with these earlier assumptions, it is estimated that the power output of a single device will average 2.97 GWh/year over the design life, if installed in a typical site off the northwest coast of Scotland. The successful installation at Aquaçadoura found that the Pelamis did perform as expected, so this assumption is still considered to be valid [13].

4 Analysis

The current study was carried out with one of the leading LCA software tools, SimaPro (version 7.2 PhD). Life cycle inventory data is mostly sourced from the Ecoinvent database, published by the Swiss Centre for Life Cycle Inventories, as this dataset is recognised as one of the most comprehensive sources of cradle-to-gate resource use and emissions data for materials, transport and other processes in Europe [2].

4.1 Goal and Scope Definition

The clear definition of a goal and scope is an integral part of any LCA [1]. The current study is intended to expand earlier work to provide an assessment of the broader environmental impacts of the Pelamis WEC, contributing to the wider body of research on the environmental impacts of power generation, and informing future design developments.

The system boundary of the current study will include the entire life cycle from "cradle-to-grave" (Figure 4). Physically the analysis includes the device, its moorings and sub-sea connecting cable, but excludes all downstream electrical components. The functional unit will be one kilowatt-hour of output power (1 kWh), with a calculation reference flow of 1 Pelamis device, producing an average of 2.97 GWh/year over its 20-year life (see section 3).

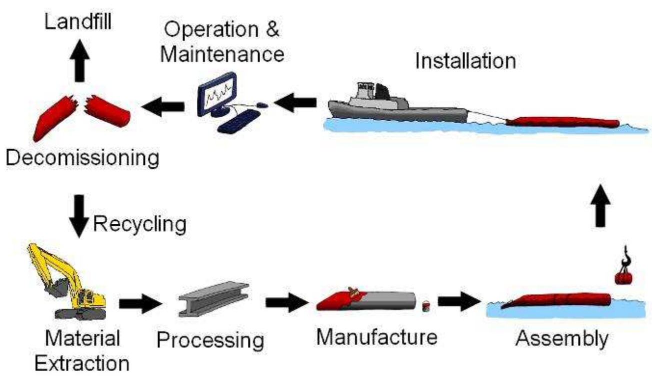

Figure 4: Pelamis Life Cycle

In line with the assumptions made by Parker *et al.* [12], the current study presents a generic case for the production of a single device, based on materials data for the first production machines. The same fixed scenario of manufacture, assembly and deployment has been defined. Later versions of the device and different installation scenarios will have different impacts to those presented here.

The current study assumes that all major components and sub-components are manufactured in the UK and subject to UK energy statistics and transport distances. It is assumed that the typical wave farm in which the device will be deployed is within 200 miles of a commercial port (implying a travel time of 24 h at 6 knots). For the purposes of calculating the carbon payback, it is assumed that the electricity offset by the device will be the average of the UK grid, with a CO_2 intensity of 0.499 kg/kWh [9].

4.2 Life Cycle Inventory Analysis (LCI)

The Life Cycle Inventory (LCI) involves detailing all resource use and pollutant emissions at each life cycle stage (Figure 4). Where data is not readily available, justifiable assumptions are made. Previous studies on other renewable energy converters have shown that the most significant impacts arise during the manufacturing stage. Care was therefore taken to gather the most comprehensive and accurate data available for this stage of the life cycle.

The current study builds upon the work carried out in 2006 by Parker *et al.*, and therefore all base data for quantities of raw materials, processing and manufacturing methods, and transportation were sourced from the same original data [12]. This was based on figures derived from PWP's own records, particularly that pertaining to the P1 device under production at the time.

Materials & Manufacture

The main structure of the Pelamis is formed from four cylindrical tube sections which increase in length from fore to aft (nose to tail). Sand ballast is placed within the tubes to optimise the buoyancy. The nose tube is tapered at one end to allow the WEC to cut through waves in rough conditions, and also houses the switchgear and transformer to collect and transform the power from the generators for export to shore. Three Power Conversion Modules (PCMs) sit between the tube sections and house the hydraulic power take-off, generators and control equipment. The Pelamis is connected to the mooring and cabling system via the Yoke, a Y-shaped element connected to the nose tube. This has a quick-release tethering system to allow for rapid attachment and detachment.

Stock Material	*Mass (kg)*
Steel	561954
Sand	475722
Stainless Steel	550
Nylon 6	416
Polyurethane	343
Glass Reinforced Plastic (GRP)	90
PVC Pipe	55

Table 1: Material quantities in the Pelamis P1

All data for the structure, hydraulic system and mooring components was based on the mass and materials of major components provided by PWP, as used Parker *et al.* [12]. A full breakdown of the materials used in the Pelamis is shown in Table 1.

Data for the resource use and pollutant emissions was sourced from the Ecoinvent database where possible [2]. This Swiss dataset provides comprehensive European average data, with UK specific data being selected where available. Data not available within Ecoinvent was sourced from alternative datasets or available literature. One example of this was sand-casting of steel components. Comprehensive data was not available within the Ecoinvent database, so data was applied from a mass balance on the British foundry manufacturing sector, carried out by Donohoe *et al.* as part of the wider Mass Balance Project [6].

In addition to the materials detailed above, over 170 different pre-fabricated components and devices are included in the Pelamis, such as fixings and electrical items. Sourcing detailed LCI data for such devices is very time-consuming, so published guidance allows for cut-off criteria to be defined so that inputs that do not have a significant environmental impact can be excluded from the study [1]. A preliminary analysis of carbon emissions and energy consumption was carried out, using cost-based analysis of the pre-fabricated components. This found that the transformer, main generators and switchboard should be included in the study, but the other pre-fabricated components combined contribute less than 1 per cent to the total impacts.

The carbon dioxide emissions and energy consumption for this life cycle stage were found to be **17 gCO_2/kWh** and **348 kJ/kWh** respectively.

Assembly and Installation

Assembly and installation processes mostly comprise transport of components from assembly plant to the dockyard, and sea vessel operations for installation of the moorings and power cabling, sea trials, initial tow to site and latching to the moorings. The analysis was based on process information provided by PWP.

In this stage the analysis method applied for transportation was different from that used by Parker *et al* [12]. Data was taken from the Ecoinvent database, with manufacturer's data being applied where appropriate. This will have introduced some variation in the results, although the base data was the same. Assembly and installation processes were found to contribute only **3 gCO_2/kWh** to the life cycle carbon dioxide emissions and require **11 kJ/kWh** of energy.

Operations and Maintenance

Annual maintenance operations will mostly involve the use of sea vessels. To date a complete picture of real operation and regular maintenance has not been registered, so data for this stage was based on estimates provided by PWP. These are understood to be conservative estimates with the key aim of confirming and ensuring survivability.

The device itself has very few operational requirements. Remote monitoring and control is entirely computer-based, onshore, so no allowance has been made for the environmental impacts of this, as it is likely to be very small.

The inventory results for this life cycle stage were higher than for assembly and installation, due to the long design life, and resulted in emissions of **7 gCO_2/kWh** and consumption of **19 kJ/kWh.**

Decommissioning and Disposal

As no Pelamis devices have yet been fully decommissioned, assumptions were made about the decommissioning and disposal processes. In line with Parker *et al.* [12] it has been assumed that decommissioning procedures will include sea vessel operations associated with the final unlatching, tow to a disposal yard and recovery of all mooring hardware.

The current study assumes that the waste will be split into two streams, with the majority of the metals (90 per cent) going on to recycling plant, and the remainder of the waste going to landfill. SimaPro contains a number of databases with information about the environmental impacts of waste treatment, but none of this is UK specific. Where available, average European data for landfill of materials was selected from the European Life Cycle Database (ELCD, v2.0), but where this was not available the figures were approximated using the Swiss data published within Ecoinvent.

The potential to recycle components can have a significant effect on the environmental impact of a device, as recycling provides the opportunity for both avoiding the environmental impacts of waste treatment and also the impacts that are associated with primary material extraction. Care must be taken to avoid double-counting that can arise when credit for recycling is assigned to both the waste material and the resulting product.

There are several different methods that can be employed for dealing with recycling within Life Cycle Assessment [8]. The current study has been carried out based on the recycled content method, as this is one of the most commonly used methods in existing published LCAs. This involves simply allocating the waste that goes to recycling to an empty process, thus removing it from the landfill waste stream. Most of the credit will actually appear in reducing the impacts associated with the materials and manufacturing stage. This is different from the method used by Parker *et al*, where recycling credit was allocated to the waste stream [12]. It is likely that this will introduce significant variations in the results.

The carbon and energy intensities at this stage are **1 gCO_2/kWh** and **3 kJ/kWh**.

4.3 Life Cycle Impact Assessment (LCIA)

The final stage of an LCA, the Life Cycle Impact Assessment (LCIA), involves classifying all of the data from the LCI and characterising it into a set of impact potentials. Although it is possible to define a proprietary impact assessment method, there are many published methods available. The key selection criteria for an impact assessment method are to ensure that it includes all relevant impact potentials, and that the number of mismatches between the inventory results and characterisation factors is minimised.

The current study applies the EDIP 2003 impact assessment method. This includes a very broad range of impact categories, in line with the goal of this study, including presenting the global warming potential in terms of mass of carbon dioxide equivalent.

5 Results

All of the results are presented per unit of energy generated by the Pelamis WEC (see section 3) in order to facilitate comparison with other generating technologies.

5.4 Inventory Results

The life cycle inventory analysis produced a list of over 1600 different types of resource use and pollutant emission. The pollutants are examined in more detail with regards to their environmental impact in the next section. Table 2 includes details of the most significant raw material consumption. (Note that gravel is a raw material used in upstream processes, but does not have significant environmental impacts.)

Raw Material	*Quantity (g/kWh)*
Gravel	13.31
Coal	8.50
Iron ore	7.56
Crude oil	4.38
Fresh water	2.97
Calcite	2.77

Table 2: Significant raw materials

The inventory also details the energy consumption associated with the life cycle of the device, and found the energy intensity to be **381 kJ/kWh** (Figure 5). This corresponds to a payback time of 25 months. Over 90 per cent of this embodied energy is associated with the manufacturing stage, mostly due to the steelmaking process.

This figure agrees well with the results presented by Parker *et al.* [12], although the increase would merit further investigation. It is likely to be due to practitioner assumptions, in particular with regards to the treatment of recycling credits.

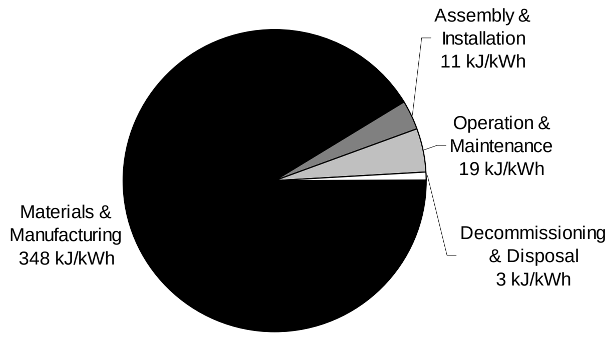

Figure 5: Embodied energy of the Pelamis WEC

In order to enable a true comparison with the figures published in Parker *et al*, the carbon dioxide emissions have also been examined at the inventory stage. Note that this does not take into account all greenhouse gases. The carbon intensity for the Pelamis is **28 gCO_2/kWh**. This is a 27 per cent increase on the earlier study, again most likely due to practitioner assumptions. Over 60 per cent of these carbon dioxide emissions are due to the manufacturing of the device, particularly in the manufacturing of the steel.

5.5 Impact Assessment

The environmental impacts of the Pelamis WEC are summarised in Table 3. It can be seen that the global warming potential (over a time horizon of 100 years) rises to **30 gCO_2e/kWh** when all greenhouse gases are included. Assuming that the carbon intensity of the offset grid electricity is 0.499 $kgCO_2/kWh$ (see section 3), full carbon payback will be achieved in 14 months.

Impact potential	*Total*
Global warming 100a	29.8 gCO_2e/kWh
Ozone depletion	2.3 µgCFC-11e/kWh
Ozone formation (Vegetation)	0.42 m^2.ppm.h/kWh
Ozone formation (Human)	2.83E-05 person.ppm.h/kWh
Acidification	2.88E-03 m^2/kWh
Terrestrial eutrophication	5.32E-03 m^2/kWh
Aquatic eutrophication EP(N)	21.0 mgN/kWh
Aquatic eutrophication EP(P)	9.84 mgP/kWh
Human toxicity air	638.9 m^3/kWh
Human toxicity water	1.59 m^3/kWh
Human toxicity soil	5.51E-03 m^3/kWh
Ecotoxicity water chronic	10.3 m^3/kWh
Ecotoxicity water acute	1.90 m^3/kWh
Ecotoxicity soil chronic	2.87E-03 m^3/kWh
Hazardous waste	2.26 mg/kWh
Slags/ashes	3.66 mg/kWh
Bulk waste	7.90 g/kWh
Radioactive waste	468.1 µg/kWh
Resources (all)	61.6 mg/kWh

Table 3: Results of life cycle impact assessment

The relative contributions of the different life cycle stages are illustrated in Figure 6. It can be seen that the manufacturing stage is a significant contributor across all categories, again mostly due to steelmaking processes, with the shipping operations associated with maintenance also contributing significantly in some categories.

An item of interest is the radioactive waste impact category. This is as a result of the nuclear energy content of electricity. An examination of the impact flow shows that 50 per cent of this is from electricity generated in France being used in the production of European steel.

5.6 Comparison with other studies

The results for carbon and energy intensity have been compared to a number of other studies, as shown in Figure 7, demonstrating that the Pelamis performs well in comparison with other technologies.

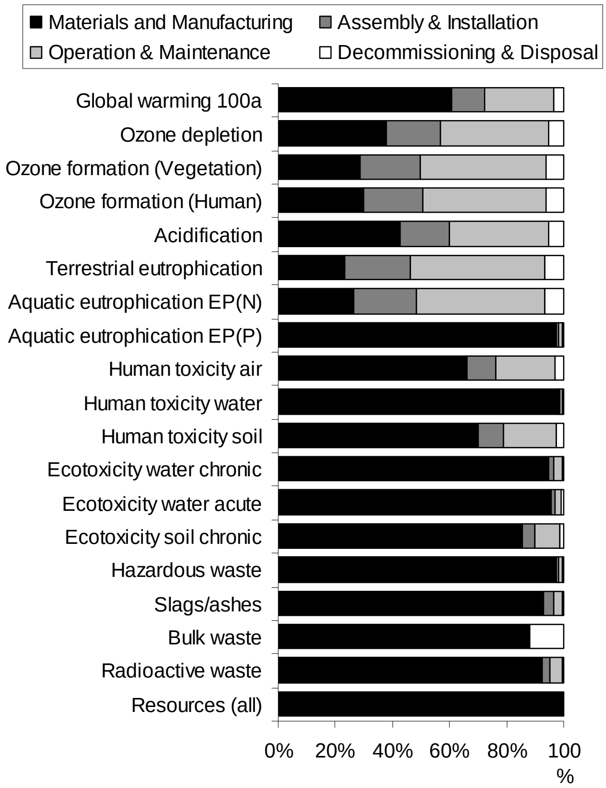

Figure 6: Life cycle stage analysis of impact potentials

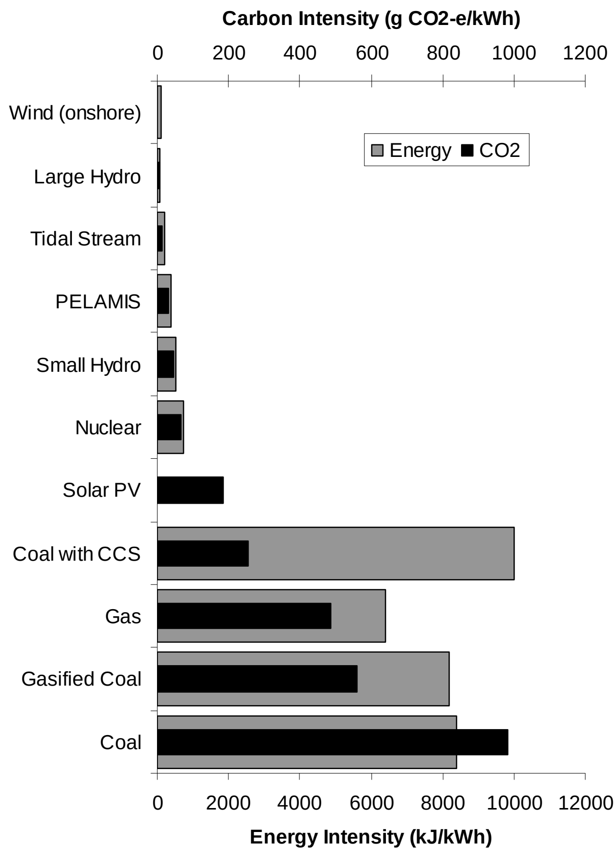

Figure 7: Comparison with other studies [7, 10, 11, 16, 17]

The results for the other impact categories have also been compared to published studies, finding that the Pelamis performs well across all environmental impacts. One such example is given in Table 4. It can be seen that the Pelamis performs significantly better than fossil-fuelled power stations with regards to pollutant emissions to the air.

Pollutant emission (g/kWh)	Pelamis	Natural gas	Coal
SO_2	0.0563	0.22	6.7
NOx	0.2052	0.61	3.35
CH_4	0.0555	2.6	0.91

Table 4: Comparison of life cycle emissions [14, 15]

5.7 Further Work

Further examination of the differences between the current study and that published in 2006 should be carried out, to identify where the variations in the results arise [12]. One priority will be to examine the effect of changing the recycling method applied in the analysis. The study could also be repeated with different impact assessment methods, to examine how these affect the results, and to expand the range of existing studies that can be compared.

6 Conclusions

The current paper presents a detailed full Life Cycle Assessment (LCA) of the first generation of the Pelamis. This builds upon work published in 2006 by Parker *et al.* [12], expanding the carbon and energy audit to a full assessment of the life cycle environmental impacts and considering emissions of all greenhouse gases. The resulting carbon intensity of 30 gCO_2e/kWh and energy intensity of 381 kJ/kWh compares well with the earlier study and published figures for other renewable energy technologies. The broader environmental impacts associated with the Pelamis also compare well with published studies for other power generating technologies.

The study also found that the most significant contributors to environmental impacts are in the steel structure and the sea vessel operations required for maintenance of the device.

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