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Life cycle assessment of ocean wave energy converter

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Summary:

Very few amounts of Life cycle assessments (LCA) are conducted for ocean wave energy converters (WEC). Among those, no work can be found regarding the oscillating water column (OWC) wave energy converter devices. This study presents a cradle-to-gate life cycle assessment for the LIMPET OWC plant. The study aims to identify the impact of the LIMPET plant. OpenLCA software was used to perform the LCA. ReCiPe 2016 and EDIP 2003 methods were used to assess the impact of the use of the Ecoinvent database. The carbon payback period and the energy payback period of the LIMPET plant were 0.14 and 161.15 years respectively. The energy payback period is very high due to inefficient energy harnessing and plant failures.

Preface

This master’s thesis was submitted to complete the Student Exchange program at the University of South-eastern Norway (USN), Campus Porsgrunn. In this thesis, a Life Cycle Assessment (LCA) of an existing oscillating water column was conducted to assess the environmental impact caused by the plant and to identify the areas that can be improved to minimize the environmental impact of the oscillating water column wave energy converters as well as other converter types.

Several software programs, such as OpenLCA open-source software and Ecoinvent database, were used for the LCA analysis. Solidworks software was also used to recreate the plant design and take measurements.

I want to express my gratitude to Associate Professor Gamunu Samarakoon Arachchige, a lecturer at USN, for giving this student exchange opportunity to the University of Sri Jayewardenepura (USJ), as well as Dr Pabasari Koliyabandara and Dr Udara Sampath for nominating me as a student exchange candidate.

So, with due regard, I express my gratitude to all who were mentioned and those I could not say by their names. Thank you all for your support and help.

Porsgrunn, 25/05/2024

Heshanka Singhapurage

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1 Introduction

1.1 Background

The growing energy demand is mostly fulfilled by non-renewable energy sources, which have many negative externalities. Hence, the use of renewable energies minimizes those negative externalities. Renewable sources like solar, wind, and ocean energies are good alternatives for traditional non-renewable energies. Literature shows that about 2 TW of wave energy is available worldwide [1].

Ocean wave energy possesses a high utilization factor, and high power density compared to other renewable energy sources. Some advantages are listed below [2].

- Ocean wave energy possesses the highest energy density among all renewable energy sources, with wave power on the sea surface about 5 times greater than wind power at 19.5 meters above the sea surface.
- Power extraction from wave energy remains continuous throughout the day, with operational efficiency reaching around 90% compared to 20% to 30% for wind and solar energy.
- The predictability of ocean wave energy enhances its appeal.
- the environmental impact remains relatively low, particularly for offshore wave devices, which exhibit the lowest impact.
- The natural seasonal fluctuations of ocean wave power align well with the electricity demand variations, further emphasizing its suitability as a renewable energy source.

Apart from that, some environmental damages are also available such as land use, construction and maintenance, coastal erosion, fish and marine biota, and noise effect [2].

Many ocean wave energy technologies are related to several factors those are water depth and location (shoreline, near-shore, offshore), as shown in Figure 1.1. In 1799 first ocean Wave Energy Converter (WEC) was patented. Since then, although hundreds of devices for harnessing wave energy have been designed and tested, most of these technologies still need improvement [2].

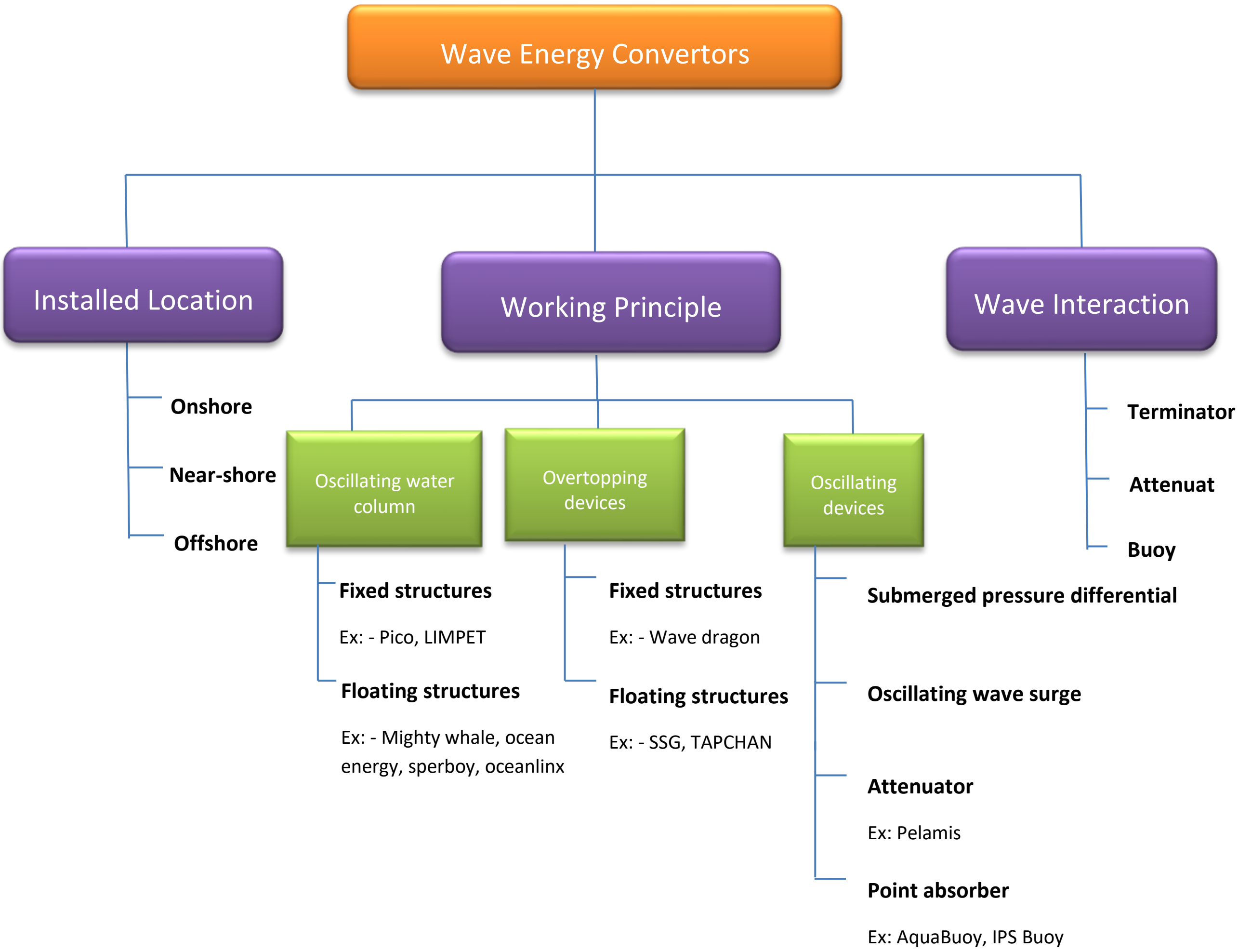

Figure 1.1 Wave Converter classification [2].

Since ocean wave energy focuses on sustainable energy production, those energy-harnessing convertors should have a low environmental impact in their entire life cycle. To estimate the environmental impact of a wave energy convertor Life Cycle Assessment (LCA) can be conducted. More about the LCA can be found in Chapter 2. LCA results allow for the identification of the main contributing phases to the potential environmental impact in the WEC life cycle allowing decisions to mitigate identified impacts through alternative material replacement, alternative design, and eco-friendly processes as such. In this thesis, cradle-to-gate LCA analysis was conducted on a selected WEC device.

1.2 Aim and Objectives

1.2.1 Aim

Conduct a cradle-to-gate LCA analysis of an Ocean WEC to identify the potential environmental impact of that WEC type and give future suggestions to mitigate the environmental impact.

1.2.2 Objectives

- To conduct a comprehensive literature review of current ocean WECs (state-of-the-art) and related LCA studies.
- To identify a WEC to conduct a LCA analysis.
- To develop a cradle-to-grave LCA model for the selected WEC.
- To suggest environmental impact mitigation solutions.

1.3 Report structure info

Chapter 02: A literature review on the ocean wave energy, WEC devices and LCA theories.

Chapter 03: Discussed the goal and scope definition, data collection, and flowchart of the system in a detailed manner.

Chapter 04: Discussed the inventory analysis phase of the LCA work.

Chapter 05: Discussed the impact assessment phase, interpreted the results generated in the impact assessment phase and discussed them.

Chapter 06: Conclusion and future works are discussed in this chapter.

2 Theoretical background and Literature review

2.1 Overview of the chapter

This chapter will discuss the theoretical background of ocean wave energy, state-of-the-art oscillating water column (OWC) devices, the LCA concept, and the LCA work carried out in the WEC field.

2.2 Introduction to Ocean Wave Energy

Ocean waves represent a plentiful renewable energy source, derived from the concentrated solar energy on the ocean's surface, driven by wind patterns resulting from the earth's uneven heating. Consequently, the energy density within water waves surpasses that of wind or solar power significantly. In Europe alone, the annual wave energy resource is estimated at approximately 720 TWh, a capacity comparable to that of traditional fuel-burning plants supplying the European electrical grid [3].

Wind-generated waves can be classified according to their appearance: linear, nonlinear, and breaking waves [4]. Figure 2.1 shows the shapes of those waves. There are several theories for modelling the above waves mathematically.

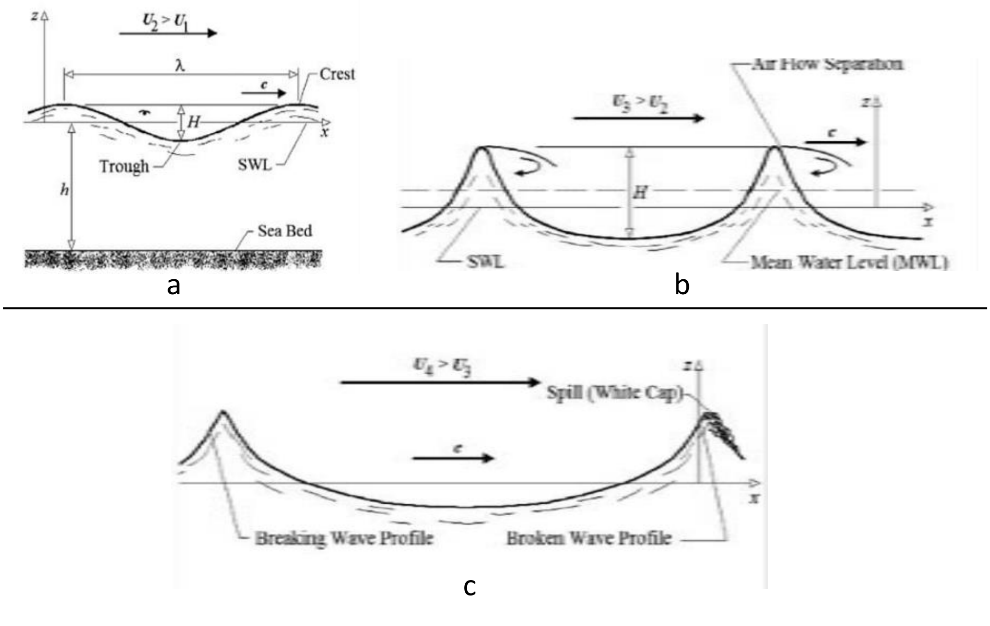

Figure 2.1 Different types of wave profiles (a) linear waves, (b) nonlinear waves, and (c) breaking waves [4].

Those theories apply to wave modelling according to the region where the waves propagate. The ocean can be divided into three regions relevant to water depth (h) and wavelength (λ) [4]. Shallow Water: h/ λ ≤ 1/20, intermediate Water: 1/20 < h/ λ < ½, and Deep Water: h/ λ ≥ ½. Figure 2.1 shows the different types of wave theories and the applicable ocean region.

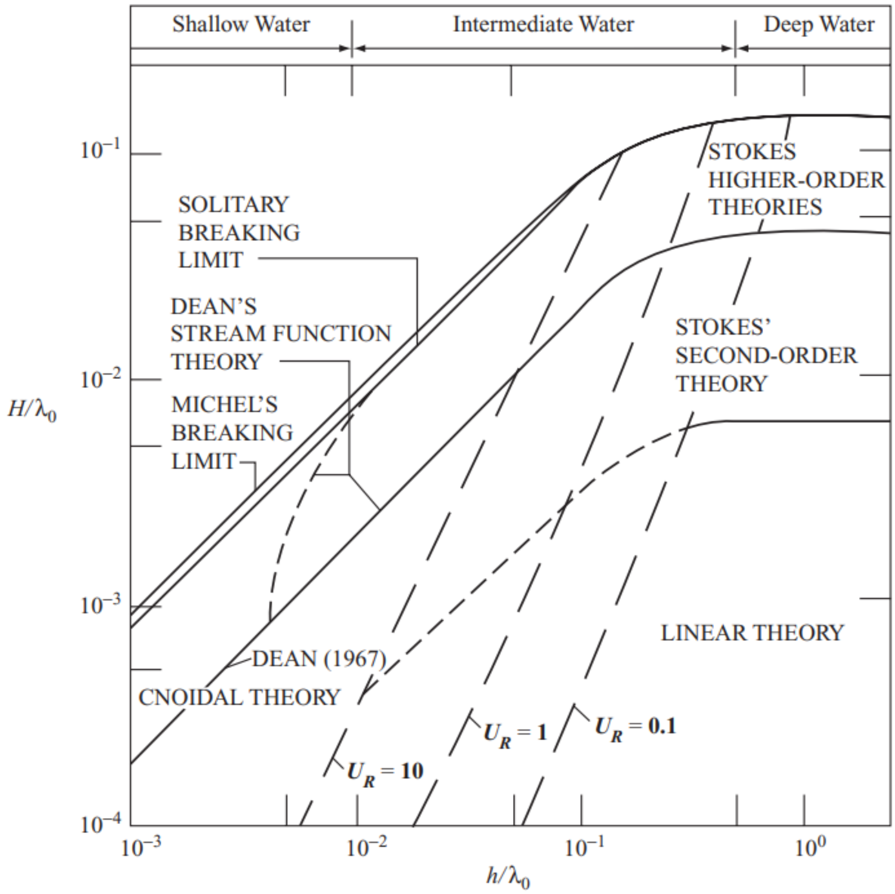

Figure 2.2 Analytical Validity Ranges of the Linear and Nonlinear Wave Theories. The Ursell parameter is UR ≡ H λ2/2h3, where H is the wave height [4].

2.2.1 Linear Wave Theory

The equations below show the formulation of the linear theory, also known as Airy's wave theory [4].

The displacement of the free surface caused by linear waves is shown in Equation (2.1).

$$\eta = \frac{H}{2}\cos[k(x - ct)] \tag{2.1}$$

Where t is time, *H* is wave height, and x is distance. The wave number k can be formulated as shown in Equation (2.2). Since the free-surface profile is sinusoidal in time and space, therefore the maximum displacement from the SWL occurs when.

$$k(x - ct) = 0, \pm 2\pi, \pm 4\pi, \ldots \tag{2.2}$$

First, when t = 0 in equation (2.2). The distance in the x-direction between two crests is the wavelength, denoted as λ. From Equation (2.2), k can be obtained as shown in Equation (2.3).

$$k = \frac{2\pi}{\lambda} \tag{2.3}$$

Next, when x = 0. The time lapse between crests is the wave period, denoted as T. From the results in Equation (2.2), we can obtain Equation (2.4).

$$kc = \frac{2\pi}{T} = 2\pi f = \omega \tag{2.4}$$

In this Equation, f gives the wave frequency in Hertz (Hz) units, and ω is the circular wave frequency. The unit is radians per second. ω is also obtained from below Equation (2.5).

$$\omega = \sqrt{gk \tanh(kh)} \tag{2.5}$$

Where g is the gravitational force.

Combining Equations (2.3) and (2.4) by eliminating the wave number yields the formula for the celerity or phase velocity by Equation (2.6).

$$c = \frac{\lambda}{T} \tag{2.6}$$

The wave velocity function of the linear wave is given by the following Equation (2.7).

$$\phi = \frac{H}{2}\frac{g}{\omega}\frac{\cosh[k(z+h)]}{\cosh(kh)}\sin(kx - \omega t) \tag{2.7}$$

Combining Equations (2.3) and (2.4), an expression for the wavelength can be obtained. This is a form of the dispersion equation that helps find the wave characteristics of the three regions of the ocean, given by Equation (2.8).

$$\lambda = \frac{2\pi}{k} = \frac{2\pi g}{\omega^2}\tanh(kh) = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi h}{\lambda}\right) = cT \tag{2.8}$$

A wave's total energy can be calculated using Equation (2.9).

$$E = \frac{\rho g H^2 \lambda b}{8} \tag{2.9}$$

Where b is the width of the wave

2.3 Oscillating water column wave energy converter

Wave energy converters (WECs) capture and convert ocean wave energy into electricity. Among WECs, the Oscillating Water Column (OWC) is widely used. It consists of a partially submerged structure with an underwater opening. As waves pass, water movement compresses and decompresses the air above, which drives a turbine connected to a generator. This process converts wave energy into electricity, giving the OWC the name "air turbine wave energy converter". The concept of wave energy isn't new. The first successful ocean wave-powered electricity generation plant was built in France in 1910, with a capacity of 1 kW. This early plant utilized air power, laying the groundwork for modern OWC systems. OWCs are simple in design, relying on natural wave movement to generate power without complex parts. With fewer submerged moving parts, OWCs are durable and easier to maintain than other WECs. They can also be scaled to meet different energy needs and environmental conditions [5].

Oscillating Water Column (OWC) wave energy devices can indeed be categorized based on installed locations into offshore, near-shore, and shoreline devices. Each category refers to the distance from the shore where the device is deployed. Offshore devices are situated farther from the coastline. Near-shore devices are located closer to the shore but still within relatively deep waters. Shoreline devices are installed along the coastline or in shallow waters. within the surf zone [5].

Ocean waves indirectly drive the turbine in Oscillating Water Column (OWC) devices. Hence, it has a longer service life compared to other Wave Energy Converters (WECs). The OWC consists of a chamber with walls that isolate the air chamber from the external environment. The incident wave drives the water inside the chamber vertically through an inlet beneath the sea. The upper part of the chamber, filled with air, is connected to a circular tube. The oscillating water surface changes the air chamber's volume, causing air to be expelled or absorbed. This airflow rotates an air turbine, which drives a coupled generator to produce electricity. Using a unidirectional rotating turbine eliminates the need for a rectifier circuit, simplifying the device.

In an Oscillating Water Column (OWC) plant, the energy conversion process unfolds in three phases. Initially, the oscillating motion of the sea surface within the air chamber transforms into pressure energy. Subsequently, this pressure energy transitions into kinetic energy. Finally, the air turbine converts this flow energy into mechanical shaft power, also known as the power take-off mechanism. Ultimately, the generator linked to the turbine transforms this shaft power into usable electrical power [6].

The most significant advantage of Oscillating Water Column (OWC) devices is that delicate mechanical components, like turbines, engage solely with reciprocating air, avoiding direct exposure to ocean waves. This indirect interaction enhances performance and reduces failure rates compared to wave energy converters directly exposed to waves. However, OWC devices do have some notable shortcomings, including:

- The construction cost is high.
- The conversion efficiency is relatively low, typically ranging from 10% to 30%.

A special type of turbine called the Wells self-rectifying turbine was patented by Queen's University of Belfast in 1977, marking a significant advancement in wave power technology. It can have unidirectional rotation for a bidirectional flow. Since 1982, six shoreline OWC prototypes have been tested in Norway, the UK, Japan, India, and China. In 1984, attention turned to shoreline WEC for island communities, leading to the launching of a 75-kW prototype plant on the Isle of Islay. [3].

The prototype plant station consisted of a reinforced concrete chamber to capture the waves, a control room, and a turbine generator unit. The wave capture chamber had a front wall inclined at 30° to the vertical, and its lower edge was positioned 1 meter below the low water level. It had a roof, a vertical back wall, and sidewalls extending to the natural height of the gully sides. The chamber measured 9 meters in length, 4 meters in width at the ground beam level, and 9 meters in height. The plan area of the water column surface varied with height and was restricted by the gully sides to an average of 20 square meters. The rear wall had two 1-meter diameter openings, one with an adjustable orifice plate and the other connected to the turbine ducting. The turbine generator unit installed at the wave power plant is depicted in Figure 2.4.

This prototype represented a significant advancement over previous systems installed in Japan and Norway in the early 1980s. It boasted mechanical simplicity and low construction costs. Additionally, it introduced several innovations. Notably, it utilized a wound rotor induction motor operating above its synchronous speed as a generator, a first in wave power plant technology. The mechanical-electrical plant featured a pneumatic actuated butterfly valve between the pneumatic chamber and the turbines, as well as a 1.2-meter diameter biplane Wells turbine directly connected to a 75-kW generator. Initially, the turbine blade sets included flywheels capable of storing 2 MJ of energy at 1500 rpm. Further enhancements included additional equipment such as a high-speed power factor correction unit and a PLC [3].

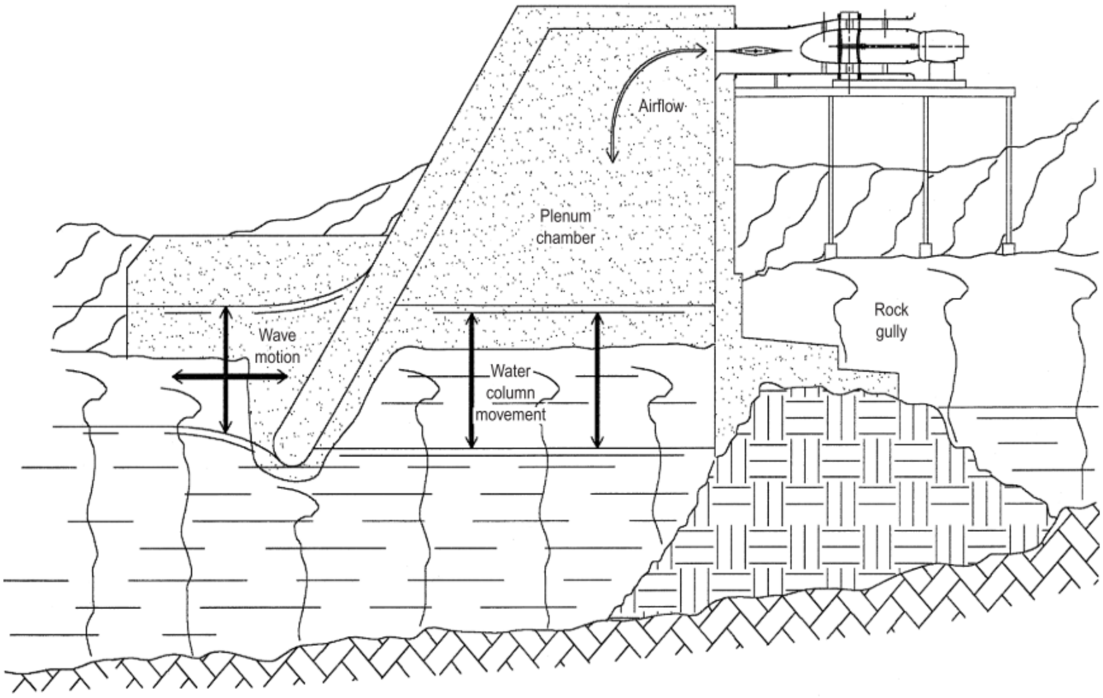

Figure 2.3 Sectional elevation of shoreline wave power plant [3].

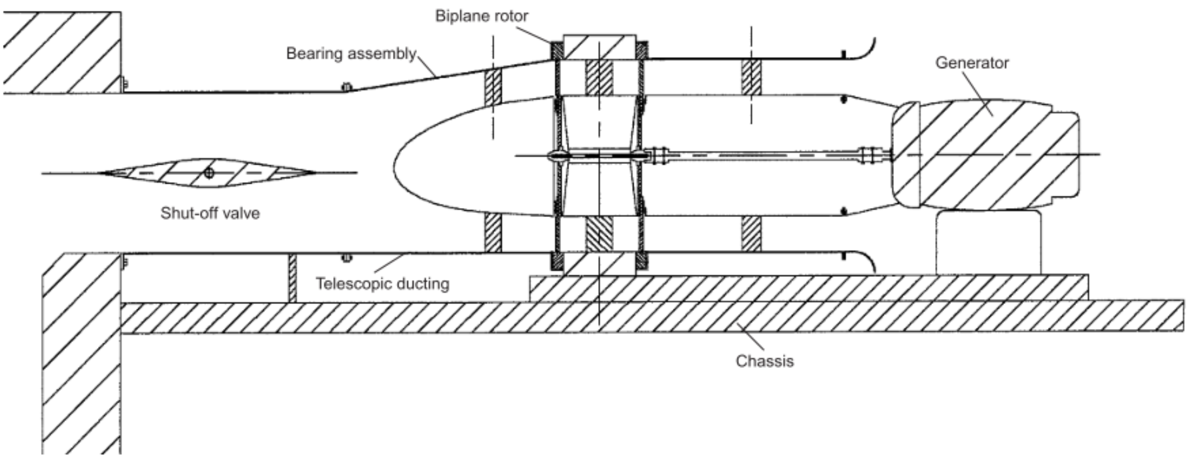

Figure 2.4 Schematic of turbine area of the prototype plant [3].

The second full-scale shoreline OWC wave energy device, named LIMPET (Land Installed Marine Powered Energy Transformer), was constructed in the UK. It was completed on the island of Islay, Scotland, marking the world's first commercial wave power station [7]. The LIMPET device comprised a rectangular inclined chamber that guided the airflow through two Wells turbines. Each turbine was connected to a 250-kW induction generator, resulting in a maximum rated power output of 500 kW for the device. Notably, the LIMPET OWC was inclined at a 40-degree angle to the horizontal, as illustrated in Figure 2.5. This configuration offered two advantages over a vertical water column, as employed in the 75 kW prototype [8].

- The inclined column and large radius front lip contribute to reducing entrance turbulence and internal sloshing, particularly significant at the shoreline due to increased surge motions relative to heave in shallow water.
- The inclination of the chamber enhances the water plane area of the water column for a given chamber cross-section.

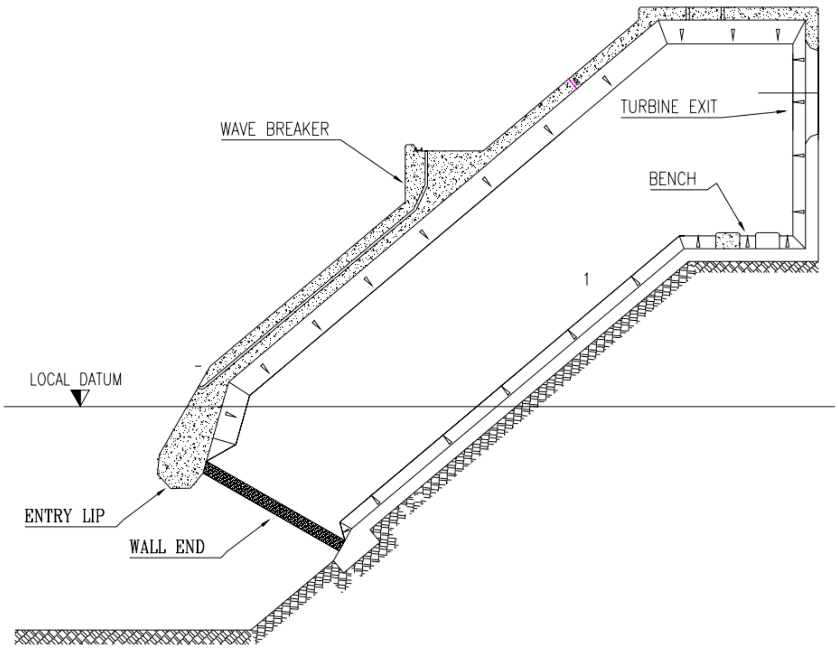

Figure 2.5 Schematic of LIMPET plant chamber [9].

When designing a wave collector, several factors are considered such as: Target power generation capacity, Environmental loads, Site Accessibility for installation and maintenance, preferred construction materials, proposed manufacturing technique, applicability of the design to a “general” site, and decommissioning. Table 2.1 shows the heights of the LIMPET power plant related to Figure 2.5.

Table 2.1 Reference Heights for the Collector [9].

Collector Roof	12.50 m
Turbine Axis	9.84 m
Top of Turbine Slab	8.30 m
Bench Level Inside Collector	4.94 m
Top of Wave Breaker on Front Wall	8.30 m
Start of 60o slope on Front Wall	2.40 m
Mean High Water Spring Tides	0.76 m
Local Datum	0.00 m
Mean Low Water Spring Tides	-1.34 m
Underside of Entry Lip	-2.63 m
Bottom of Diaphragm Walls	-4.52 m
Seabed under Lip	-7.00 m

2.3.1 LIMPET OWC efficiency and operating data

An ultrasonic sensor and pressure transducer were used to measure the water displacement inside the chamber. Figure 2.6 shows the water displacement data of the LIMPET power plant.

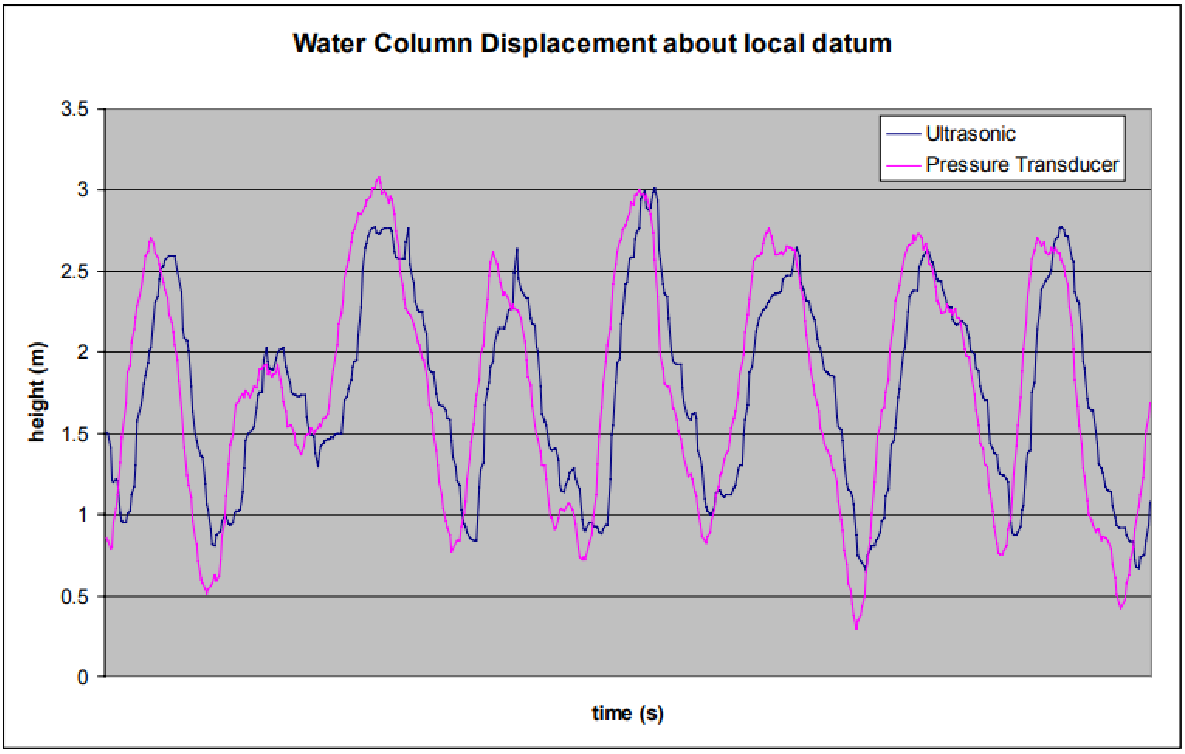

Figure 2.6 Comparison of Water Column Displacement LIMPET power plant [9].

The counter-rotating Wells turbine's performance did not meet the expected power generation capacity due to the unpredictable oscillatory behavior of the flow through the turbine driven by waves. This unpredictability resulted in an earlier onset of stall in the turbine than when the flow is steady and unidirectional. Consequently, the stall diminished the turbine's efficiency. This notable difference in the turbine's performance between unidirectional and oscillating flows was not previously observed [9]. Due to the lack of appropriate oscillating flow facilities for testing the turbine, it was impossible to predict this effect. Additionally, the increased occurrence of turbine stalls necessitated the installation of a larger silencer. To mitigate this issue, a noise attenuation chamber was retrofitted onto the end of the turbine ducting. While this chamber did not cause a significant pressure to drop, studies of the flow distribution around the turbine ducting revealed that it caused a maldistribution of flow during the intake stroke of the turbine. This led to increased airflow at the bottom of the turbine ducting, worsen the stall phenomenon and resulting in a reduction in turbine performance, as depicted in Figure 2.7.

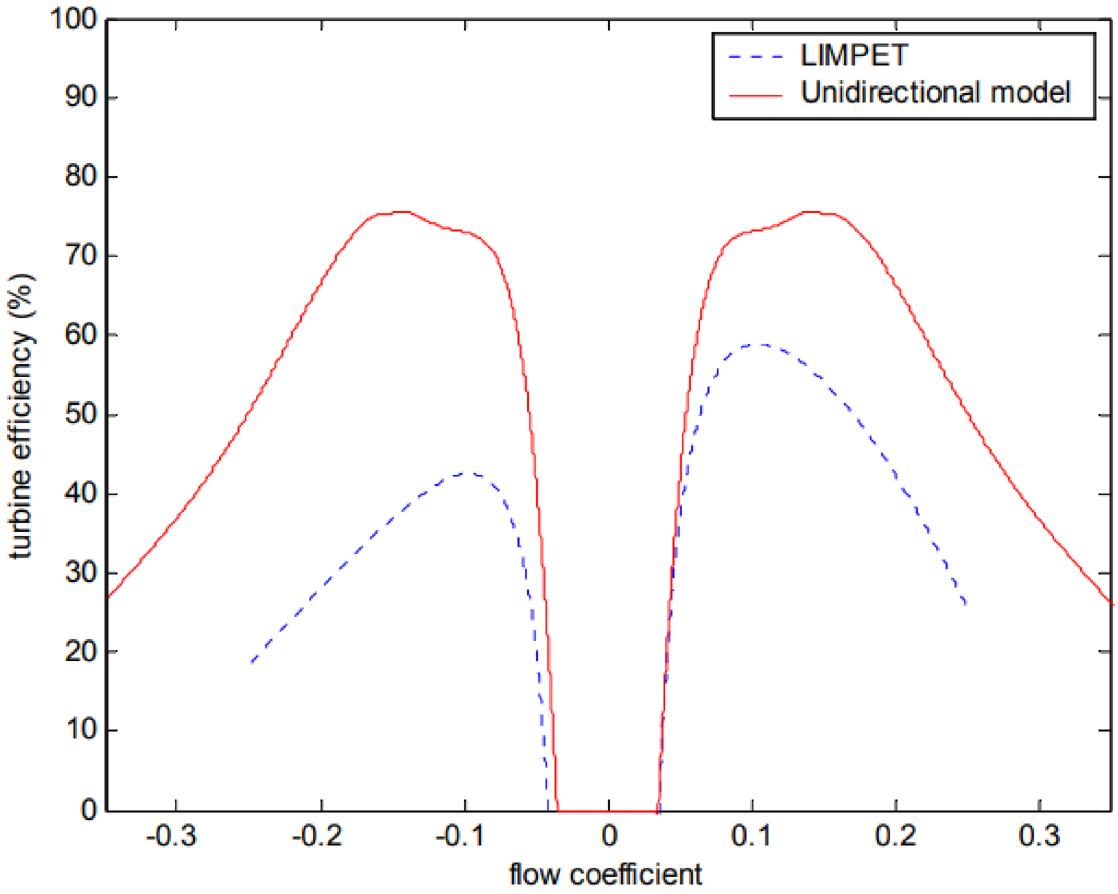

Figure 2.7 Turbine Efficiency vs Flow Coefficient for Predicted and Actual [9].

The average cyclic efficiency of the turbine depends on the wave climate. Data from the plant shows an average turbine efficiency of around 35%. The red line in the graph represents turbine efficiency from unidirectional model tests. It indicates that the earlier stall onset reduces peak turbine efficiency, while the dashed blue line shows a narrowing of turbine bandwidth.

2.3.2 Current status of Wells Turbine

The Wells turbine, being a reaction turbine, has inherent drawbacks such as lower efficiency, poorer starting characteristics, and higher noise levels than conventional turbines. Numerous experimental and computational studies have been conducted on various performance parameters and alternative methods to address these weaknesses to enhance Wells turbine performance. These efforts have led to improvements in the mentioned parameters, and several configurations of the Wells turbine have been thoroughly investigated [7].

- Wells Turbine with Guide Vanes
- Wells Turbine with Self-Pinch Controlled Blades
- Biplane Wells Turbine
- Contra Rotating Wells Turbine
- Wells Turbine with Booster Turbine
- Wells Turbine with End Plates

2.4 LCA concept and methodology

Life cycle assessment (LCA) is a decision-making tool which analyses the environmental impact of a good or service based on a specific function throughout their entire lifetime or the different stages of their lifetime. Paving the way to distinguish the stages where improvements in the environmental point of view can be made in a product or service. LCA can be combined with an economic analysis, a technical analysis, or a social analysis, thereby integrating the various aspects of sustainability [10].

Life Cycle Assessment (LCA) stands apart from other environmental-related methods by establishing a link between environmental performance and functionality. It quantifies emissions and resource extraction (raw material usage) based on the function of the system or product throughout its entire life cycle. This approach provides a comprehensive understanding of the environmental impact associated with a product or system, from raw material extraction to disposal or recycling [10].

Life Stages of a product or services can be divided into sections for LCA analysis as follows [10].

- Cradle-to-Grave (Entire life cycle)
- Cradle-to-Gate (From raw material extraction to specific life stage)
- Gate-to-Gate (From a specific life stage to another specific life stage of the same product or service)
- Gate-to-Grave ((From specific life stage to end of life stage)

According to ISO standards, LCA consists of four phases which are goal and scope definition, inventory analysis, impact assessment, and interpretation. Since this is an iterative process, the scope can be changed during the analysis. Figure 2.8 shows the four phases of the LCA.

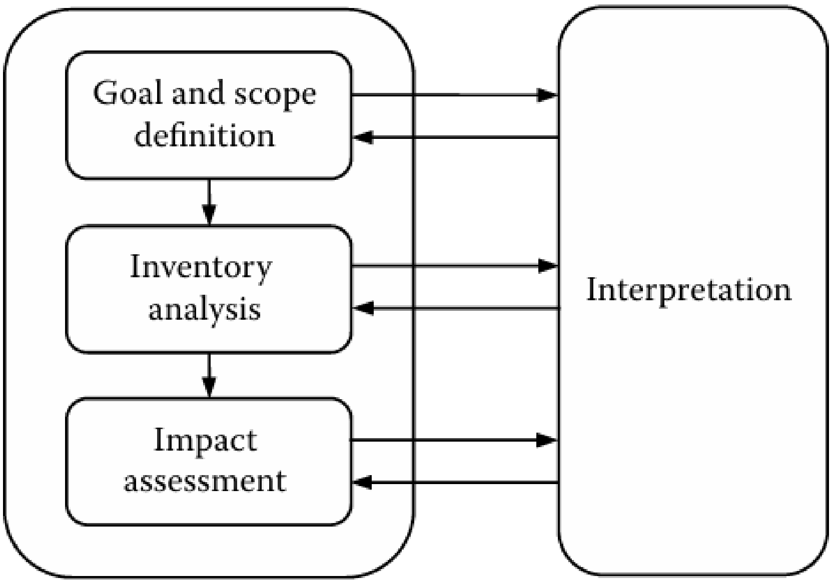

Figure 2.8 The four iterative phases of life cycle assessment [10].

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2.4.1 Introduction to Goal and Scope Definition

ISO 14044 guides defining the goal and scope of a life cycle assessment (LCA), including the following items [10]:

2.4.1.1 Goal Definition:

Intended Application: Specify how the LCA results will be used, typically for decision-making, product improvement, or other purposes.

Reasons for Carrying Out the Study: Clearly state the motivations behind conducting the LCA, such as compliance with regulations, product development, or environmental performance improvement.

Intended Audience: Identify the target audience for the LCA results. Typically, it's internal stakeholders, regulatory authorities, customers, or the public.

Comparative Assertions: Determine if the results will be used to make comparative claims or disclosed to the public for comparison with similar products or processes.

2.4.1.2 Scope Definition:

Product System: Define the boundaries of the product system intended to be studied. It includes all relevant processes, inputs, and outputs.

Function of the System: Describe the primary function of the product system intended to be assessed, such as energy generation, transportation, or manufacturing.

Functional Unit (FU): This is used as a reference unit of quantified product system performance.

System Boundary: The system boundary includes all life cycle stages from raw material extraction and user phase to end-of-life.

Allocation Procedures: Inputs and outputs are shared among multiple products or processes.

Life Cycle Impact Assessment (LCIA) Methodology: Select the LCIA methodology and types of impacts.

Interpretation: Elaborate the methods for interpreting the results and drawing conclusions from the LCA findings.

Data Requirements: Specify the data required for the assessment such as primary data collection, and secondary data sources.

Assumptions: State any assumptions made during the assessment process.

Value Choices and Optional Elements: Address any value choices or optional elements that may affect the results, such as system boundaries or impact categories.

Limitations: Identify the constraints and uncertainties associated with the analysis.

Data Quality Requirements: Specify the level of data quality required for the assessment. It includes data reliability, completeness, temporal, geographical, and technological correlations.

The system may consist of multiple unit processes designed to achieve its intended function. Each process involves inputs and outputs: inputs are resources extracted from the environment, such as energy and land, while outputs are emissions released into the air, water, and soil. In the economic realm, the output of the system is the service provided by the product. Unit processes within the system are interconnected through intermediary flows, establishing a network that enables the system to function as a whole [10]. Figure 2.9 shows the flowchart of a system. The flowchart provides a clear overview of the processes and their relationships.

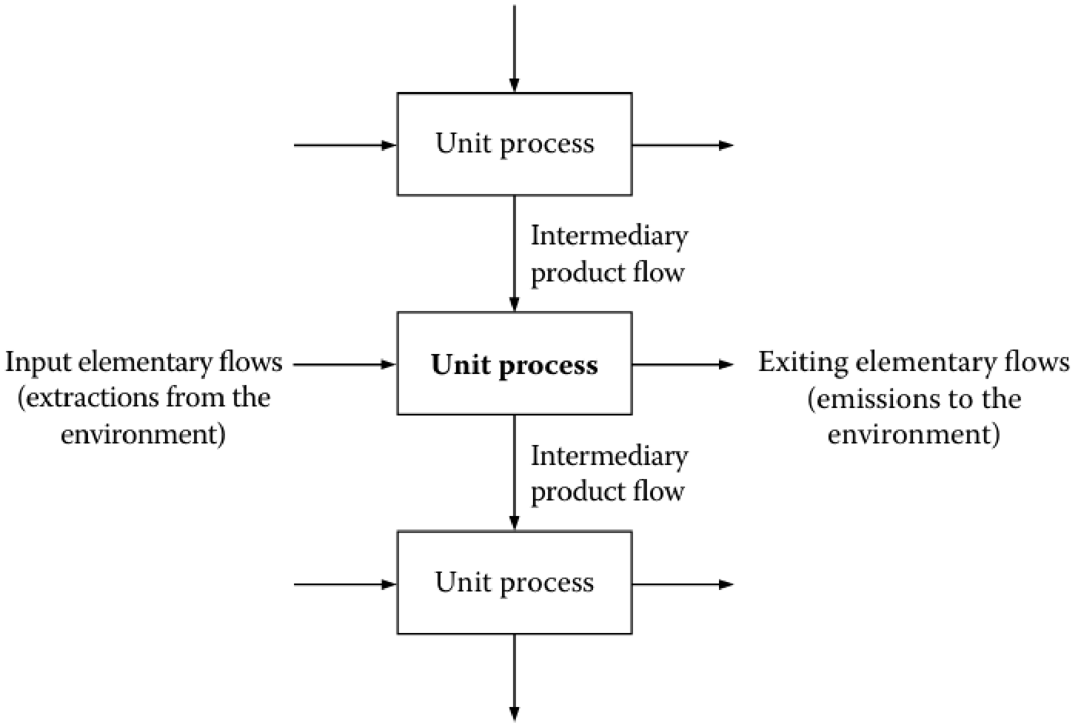

Figure 2.9 Example of a set of unit processes in a system [10].

2.4.2 Introduction to Inventory Analysis

There are two approaches available to calculate inventories. The process-based approach and the input-output (I/O) approach are two methodologies used in inventory analysis, particularly in life cycle assessment (LCA). Here, the process-based approach is focused, which relies on detailed modelling of physical flows. The steps below outline how to conduct a process-based inventory analysis [10]:

Start with Reference Flows Corresponding to the Functional Unit (FU):

- Identify the reference flows corresponding to the functional unit, which is a quantified description of the performance requirements the product system must fulfil.
- Design a flowchart of the core unit processes involved in the system, mapping both upstream (supply chain) and downstream (use and disposal) processes. This should include intermediary flows of materials and processes associated with each reference flow.
- Continue mapping until you link the processes to those existing in a database, which acts as a stopping criterion.

Identify Inputs and Direct Emissions for Each Unit Process:

- For each identified unit process, determine its inputs in terms of quantified intermediary flows and its direct emissions (elementary flows).
- These inputs and emissions can be sourced from:
  a) Existing databases.

b) Measurements and empirical data.
c) Direct communication with companies involved in the process.

Document Data on Flowchart or Table:

- Create documentation (flowcharts or tables) that describe the sources of information used for each unit process.
- Ensure all data points, including the origin and reliability of the data, are well-documented for transparency and reproducibility.

Calculate Emissions for Each Unit Process:

- Multiply the amount of each unit process per functional unit by its respective emission and extraction factors.
- This step involves quantitative analysis to convert process inputs into corresponding environmental impacts.

Aggregate Total Emissions and Extractions:

- Sum all elementary flows (emissions and extractions) from all unit processes involved in the product system.
- This aggregation provides a comprehensive view of the total environmental impact associated with the functional unit.

By following these steps, the process-based approach facilitates a detailed and transparent analysis of the environmental impacts associated with a product or service, allowing for targeted improvements and informed decision-making. Databases such as Ecoinvent can be used for a process-based approach.

2.4.3 Life Cycle Impact Assessment

The third phase of The LCA is the life cycle impact assessment (LCIA), conducted after gathering all the data related to raw material extractions and substance emissions throughout a product's life cycle.

Initially, inventory results with similar effects are grouped into an impact category at an intermediary level, known as a midpoint category. For each midpoint category, a midpoint indicator is established. To assess the contribution of each inventory flow to the midpoint category, each flow is multiplied by a characterization factor (CF). This step characterizes the environmental impact of the inventory flows within that specific midpoint category.

Subsequently, each midpoint category is allocated to one or more damage categories, representing various protection areas such as ecosystems and human health (HH). These damage categories are illustrated by a damage indicator, also known as an endpoint indicator. Figure 2.10 provides an overview of the general structure of the UNEP-SETAC impact assessment framework, illustrating the relationship between midpoint and damage categories.

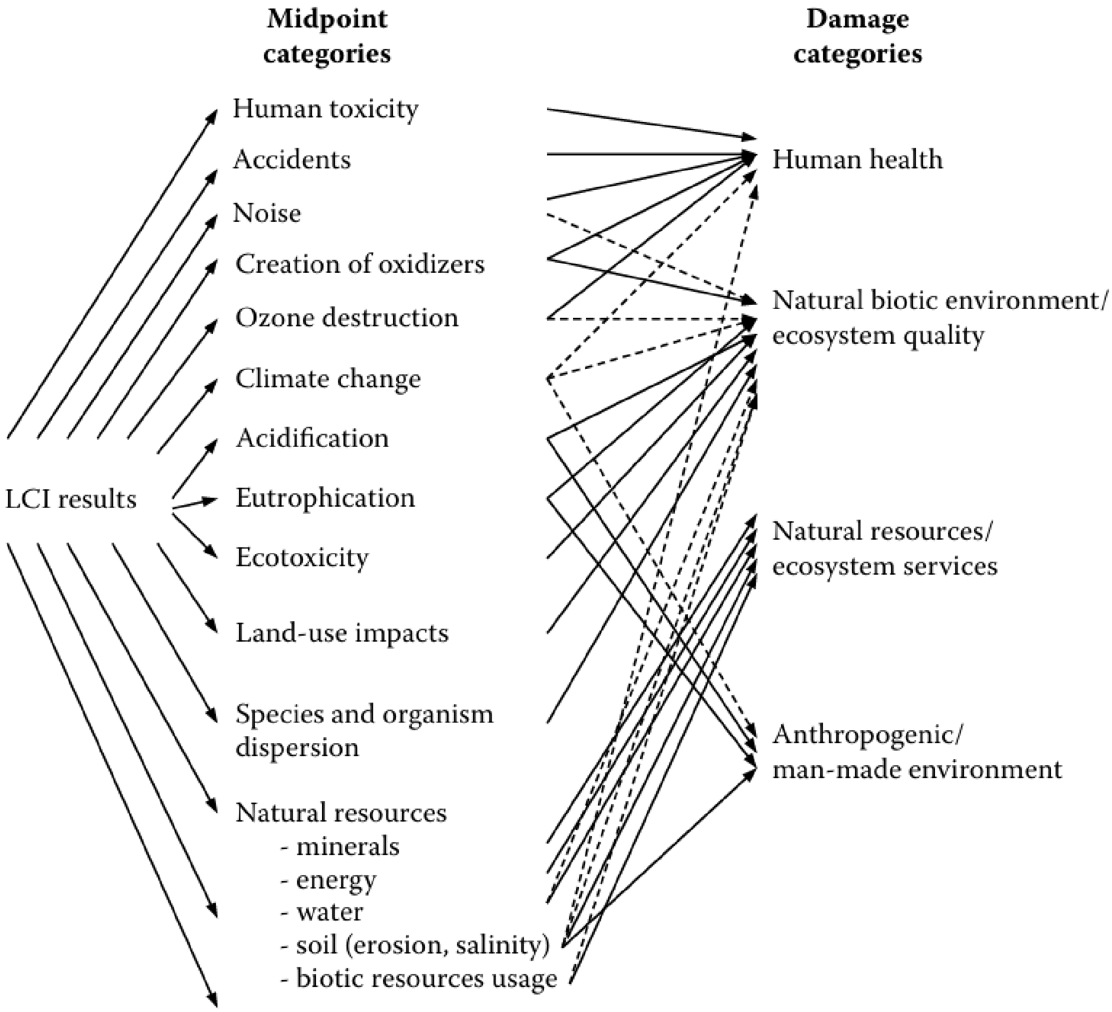

Figure 2.10 the structure of the UNEP-SETAC LCIA method.

Midpoint scores can be calculated for different emissions and extractions are weighted to represent their contribution to each midpoint category. The emission extraction contribution at the midpoint level can be calculated using Equation 2.10.

$$s_m{}^{midpoint} = \sum_i (CF_{m,i}{}^{midpoint} * u_i) \qquad (2.10)$$

where:

$s_m{}^{midpoint}$ is the midpoint score.

$CF_{m,i}{}^{midpoint}$ is the midpoint CF of substance “I” in the midpoint category m.

u_i is the emitted or extracted mass of substance “I” per functional unit as given in the inventory.

Using either midpoint to-damage characterization factor (MDF) or damage characterization factor, endpoint contribution of emission and extraction can be calculated using the below equations.

$$s_d^{damage} = \sum_m (MDF_{d,m} * s_m^{midpoint}) \quad (2.11)$$

$$s_d^{damage} = \sum_i (CF_{d,i}^{damage} * u_i) \quad (2.12)$$

Where,

s_d^{damage} is damage score.

$CF_{d,i}^{damage}$ is endpoint characterization factor.

To calculate the impact different types of impact methods are available with different types and different amounts of impact categories. These impact methods have their own CF values. One can be selected according to the LCA application. ReCiPe, IMPACT world+, Cumulative Energy Demand (CED), and EDIP2003 are some of examples impact assessment methods. Most of the published LCAs regarding WECs used ReCiPe 2016 methods.

2.4.3.1 ReCiPe 2016 method

ReCiPe 2016 method is one of the impact assessment methods. It has three types according to time horizon. Those are Individualist for 20-year time horizon, Hierarchist 100-year time horizon, and Egalitarian 1000-year time horizon [11]. Figure 2.11 shows the impact categories of the ReCiPe 2016.

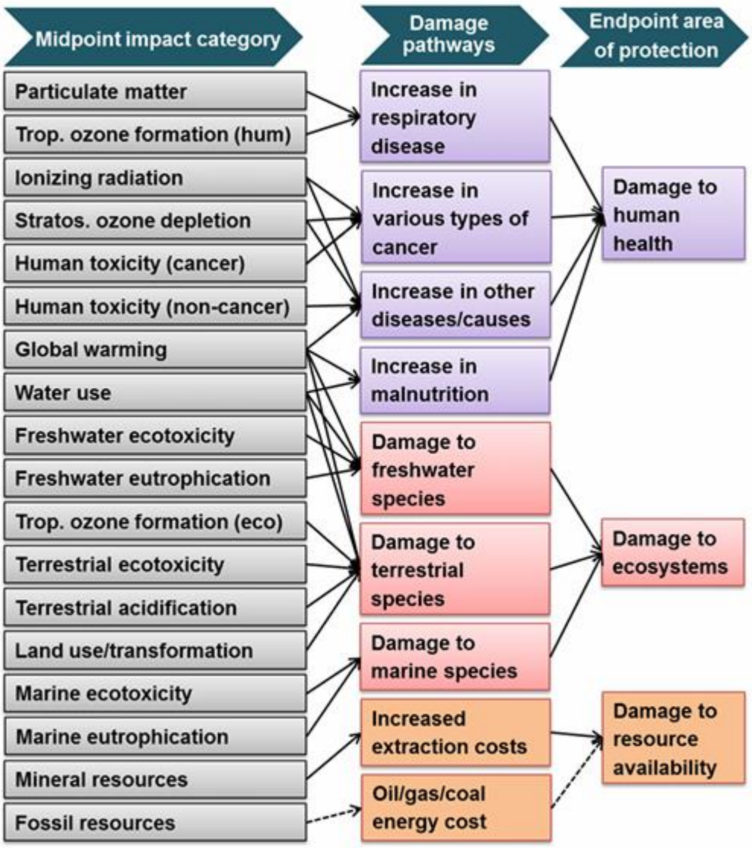

Figure 2.11 Overview of the impact categories covered in the ReCiPe 2016.

2.5 Research works published.

There are few numbers of research can be found regarding LCA on ocean wave energy converters.

A cradle-to-grave LCA was performed for a Pelamis P1 wave energy converter, encompassing its mooring and subsea connecting cable. Foreground data primarily came from the manufacturer, while background data was taken from the Ecoinvent database (v3.3). The ReCiPe and Cumulative Energy Demand (CED) impact assessment methods were used to calculate the environmental impacts.

The functional unit for this LCA is 1 kWh of output electrical power, with a reference flow of the Pelamis unit. The study identified that most of the environmental impact originated from steel manufacturing and sea vessel operations. These activities contribute significantly to the overall environmental footprint of the wave energy converter.

The findings show that the deployment and maintenance of offshore wave energy converters have considerable environmental impacts. This is because of the large use of steel and the operational demands of the sea vessels involved [12]. Figure 2.12 shows the component of the Pelamis OWC

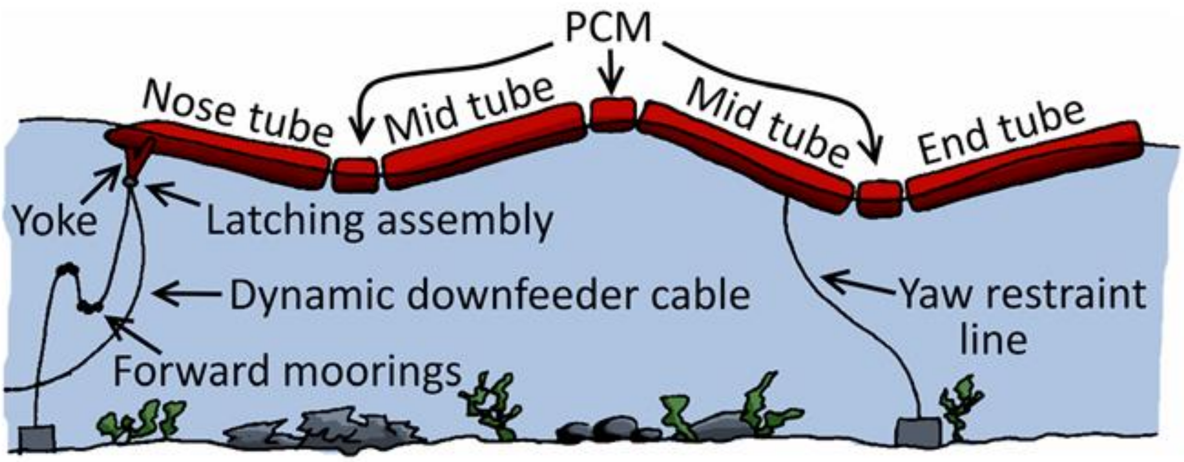

Figure 2.12 Component of the Pelamis [12].

A cradle-to-grave life cycle assessment (LCA) was carried out for the Oyster 1 and Oyster 800 wave energy converters (WECs), with the functional unit defined as 1 kWh of output electrical power. Hence all impacts were reported per unit of energy output. The primary impact assessment methods employed were EDIP2003 and Cumulative Energy Demand (CED), with ReCiPe2008 also utilized for comparative analysis. Background data was obtained from the Ecoinvent database, and several assumptions were made for simplicity [13]:

1. Since the Ecoinvent database does not have data on marine-grade steel, stainless steel material was approximated.

2. Small mechanical components and onshore assembly data were excluded from the analysis, assuming the impacts of those components are relatively insignificant.

The LCA results revealed significant environmental impacts associated with stainless steel usage. Specifically, the carbon footprint and energy payback period were measured. It was 79 and 57 gCO2 eq/kWh, and 45 and 42 months for the Oyster 1 and Oyster 800, respectively. The substantial mass of the structures emerged as a primary driver of environmental damage across various impact categories, mainly due to the extensive utilization of steel. The prominent use of stainless steel significantly contributed to the overall environmental footprint, underscoring the importance of material optimization and exploring alternative options to mitigate the environmental impact of these wave energy converters [13].

This analysis underscores the importance of considering material choices and mass reduction strategies in designing and deploying marine energy technologies to enhance their sustainability and reduce their environmental impact. Figure 2.13 shows the sketch of the Oyster wave energy converter.

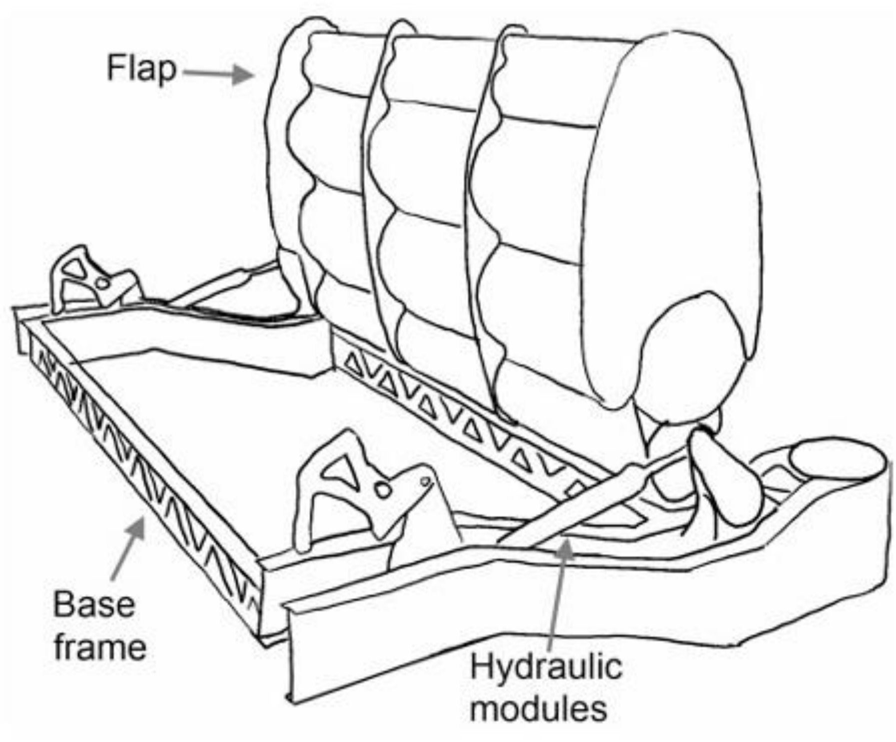

Figure 2.13 Sketch of the Oyster OWE

Another study presents the LCA analysis for a point absorber type WEC called buoy-rope-drum (BRD). It has a capacity of 10 kW. The embodied energy and emissions from raw materials data were based on normalized values from the Ecoinvent 3 database.

The ReCiPe midpoint level method was applied for the life cycle impact assessment (LCIA). 1 kWh of electricity was chosen as the functional unit. It is convenient for comparison of LCA results across different wave energy converter technologies. Researchers can directly compare the environmental impacts, energy intensities, and carbon footprints of various wave energy converters [14].

The study calculated the energy intensity and carbon intensity as 387 kJ/ kWh and 89 gCO_2/kWh respectively. The energy payback period, which is the time required for the WEC to generate the amount of energy equivalent to that consumed during its life cycle. It was 26 months. Similarly, the carbon payback period, which is the time required for the WEC to offset the carbon emissions generated during its life cycle, was determined to be 23 months [15].

These results indicate that the BRD WEC has favorable energy and carbon payback periods. Figure 2.14 shows the BRD WEC.

Figure 2.14 BRD WEC deployment phase photograph [15].

Another study shows the environmental impacts of a 10 MW array of 28 point-absorber WECs using a process-based life cycle assessment (LCA). The study presents ReCiPe v1.31 midpoint (H) and Cumulative Energy Demand (CED) LCA results across 19 impact categories. This LCA was Conducted at an early stage of the wave energy converter's product development.

The functional unit for this LCA is defined as 1 kWh of electricity generated by the wave energy array, allowing for direct comparison with other wave energy technologies. Several assumptions were made in the study, with the main one being the amount of steel removed during machining processes, set to 23% based on Ecoinvent recommendations. Additionally, the study considered marine operation requirements, generation, and failure modes.

The study highlights that while comparing different technologies is useful for context, it is crucial to ensure a consistent scope of analysis when making direct comparisons between LCA studies. Results from this LCA are particularly valuable at the early stages of technology development for ocean wave energy, as they can inform design considerations and help recognise hotspots of particular impacts, which can then be mitigated in future iterations of the technology [16]. Figure 2.15 shows the point absorber WEC.

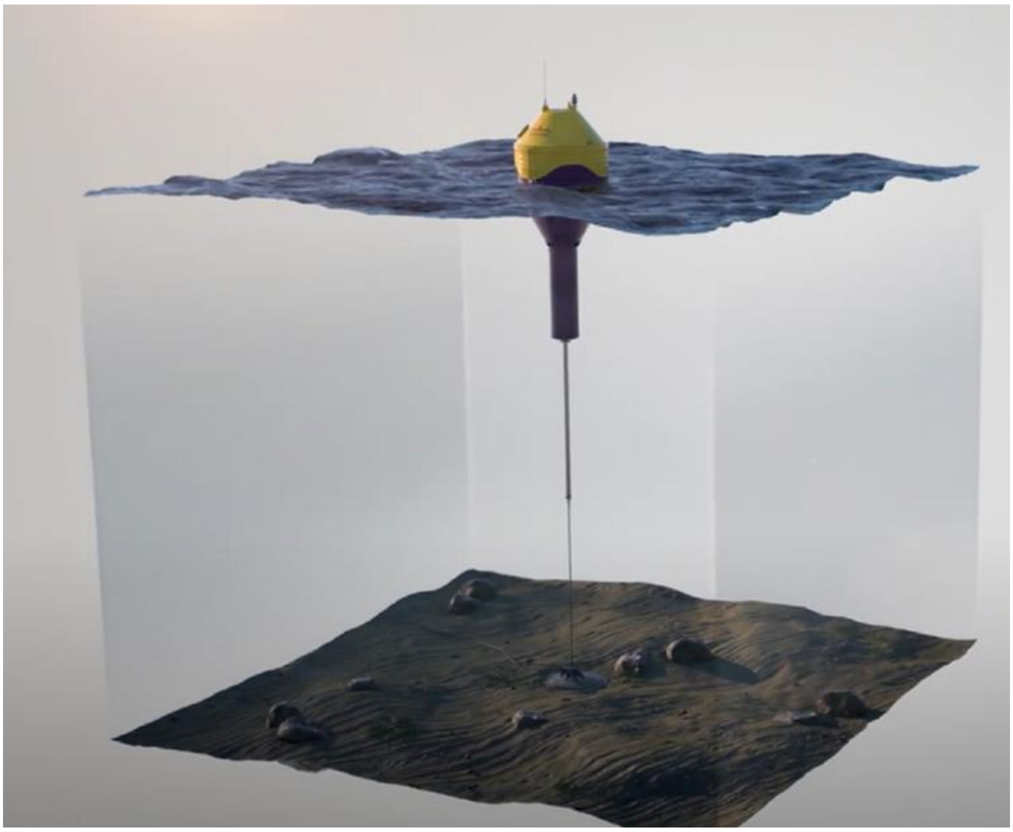

Figure 2.15 Illustration of CorPower Ocean WEC [16].

Figure 2.16 shows a summary of the discussed research works mentioning the functional units, the database used, and the impact assessment used. Further research work can be found in [17],[18], and [19] for different wave energy converters

An obvious gap can be identified when referring to the published works which is no LCA work can be found for Oscillating water column-type (OWC) wave energy converters. OWC devices

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Life cycle assessment of a point-absorber wave energy array

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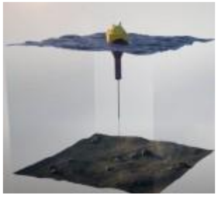
- 10 MW array of 28 point -absorber wave energy converters
- Device rating 350 kW
- The functional unit is defined as1 kWh of electricity generated by the wave energy
- The impact assessment methods used for this study are ReCiPe v1.31
- SimaPro v9.1.0 software was used
- Ecoinventdatabase v3.6



energies

MDPI

Article

Life Cycle Assessment of a Buoy-Rope-Drum Wave Energy Converter

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- The designed rated power capacity is 10 kW
- Functional unit of this LCA study is thus defined as the entire BRD WEC system during its service lifespan of 20 years.
- The ReCiPe method is applied for the LCIA at a midpoint level
- SimaPro v 8.3.0.0
- Ecoinvent 3 database

The International Journal of Life Cycle Assessment (2019) 24:51–63
https://doi.org/10.1007/s11367-018-1504-2

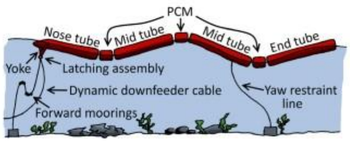
LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

An LCA of the Pelamis wave energy converter

R. Camilla Thomson [1] · John P. Chick [1] · Gareth P. Harrison [1]

Received: 26 November 2017 / Accepted: 10 July 2018 / Published online: 23 July 2018

- Rated power of the convertor 750 kW
- Cradle-to-grave
- SimaPro (version 8.3 PhD)
- ReCiPe and CED impact assessment methods were applied
- Ecoinvent database (v3.3)
- The functional unit is 1 kWh of output electrical power, with a reference flow of one Pelamis
- **Conclusion-** Steel production and processing has a significant impact in virtually all categories, The environmental impacts of operating sea vessels are also significant within the life cycle of the Pelamis



Full life cycle assessment of two surge wave energy converters

Hakan Karan, R Camilla Thomson and Gareth P Harrison

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- The first-generation device, the Oyster 1, was rated at 315 kW, while the secondgeneration Oyster 2 is rated at 800 kW
- SimaPro 8 is used
- ReCiPe 2008, EDIP2003 and Cumulative Energy Demand (CED) impact assessment methods were applied
- The functional unit was chosen as 1 kWh
- Ecoinvent v3.01,
- **Conclusion-** The high mass of the structures was found to cause the greatest environmental damage across most impact categories due to the extensive use of steel

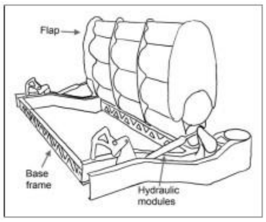


Figure 2.16 Summary of the literature published LCA works of WECs.

3 LCA goal and scope definition

3.1 Overview of the Chapter

In this chapter first phase which is the goal and scope definition was discussed. Further, what is the intent of this research, what is the boundary considered for the LCA and what wasn't taken into account was discussed. Finally, the system flow chart also was discussed.

3.2 Objective

Since there is no published LCA for oscillating water column wave energy converter this thesis objective is to conduct a cradle-to-gate LCA to analyze the environmental impact of the LIMPET oscillating water column power plant and identify the most impactful process and flows.

3.3 Functional unit and reference flow

The functional unit 500kW oscillating water column power plant is defined and Reference flows are the manufacturing of the mechanical-electrical plant and construction of the chamber structure.

3.4 System Boundaries

This is a Cradle-to-gate analysis. The life cycle can be divided into several sections as follows and Figure 3.1 shows the process flow of the selected system. Raw material excavation, transportation, and processing.

- Site excavation and waste gravel transportation.
- Chamber material transportation and construction.
- Electrical-Mechanical plant equipment manufacturing, and transportation of equipment to the plant site.

The processes that are not considered in the life cycle are:

- The production of small components such as bolts, rivets, cables, and electronic parts (sensors).
- Assembly of the electrical-mechanical plant, and construction effort of the chamber structure.
- Connection to the power grid.
- Operation and maintenance.
- Decommissioning of the plant.

- End of the life of the material of the plant.

As can be seen in the process flow chart the LIMPET plant can be subdivided into two main reference flows such as OWC chamber construction, and the Electrical-mechanical plant. Those reference flows consist of several processes and related inputs and outputs. More details of those processes can be found in Chapter 4.

In the OWC chamber construction, the first reference flow to the LIMPET plant, several unit processes are involved, each contributing to the construction of the chamber. These processes include:

1. Site Excavation: Excavation of the site where the OWC chamber as was constructed.
2. Steel Plate Production for Entry Lips and Diaphragm Walls: Production of steel plates used for entry lips and diaphragm walls, essential components of the OWC chamber.
3. Transportation of Reinforced Concrete: Transporting reinforced concrete to the construction site.
4. Gravel Transportation: Transportation of gravel from the excavated area, although its output is not part of the final process.

In the electrical-mechanical plant construction, the second reference flow, unit processes involve the production of various components essential for the plant's operation:

1. Production of Turbine: Manufacturing of the turbine. Power take-off system for converting wave energy into mechanical energy.
2. Production of Flywheels: Manufacturing of flywheels. This is for energy storage or stabilization.
3. Production of Duct: Manufacturing of ducts. Act as a channel to maintain air flow within the system.
4. Production of Valves: Manufacturing of valves for controlling flow.
5. Production of Turbine Stands: Manufacturing of stands to support the turbines.

After these processes, all outputs are connected to a transportation method to transport the components to the area where the plant was constructed.

In the flow chart:

- The main inputs are colored orange.
- Waste streams are colored black.
- Outputs are colored green.
- Processes are colored in ash color.

This flow chart provides a clear visualization of the construction processes involved in building both the OWC chamber and the electrical-mechanical plant, highlighting the inputs, outputs, and waste streams associated with each unit process.

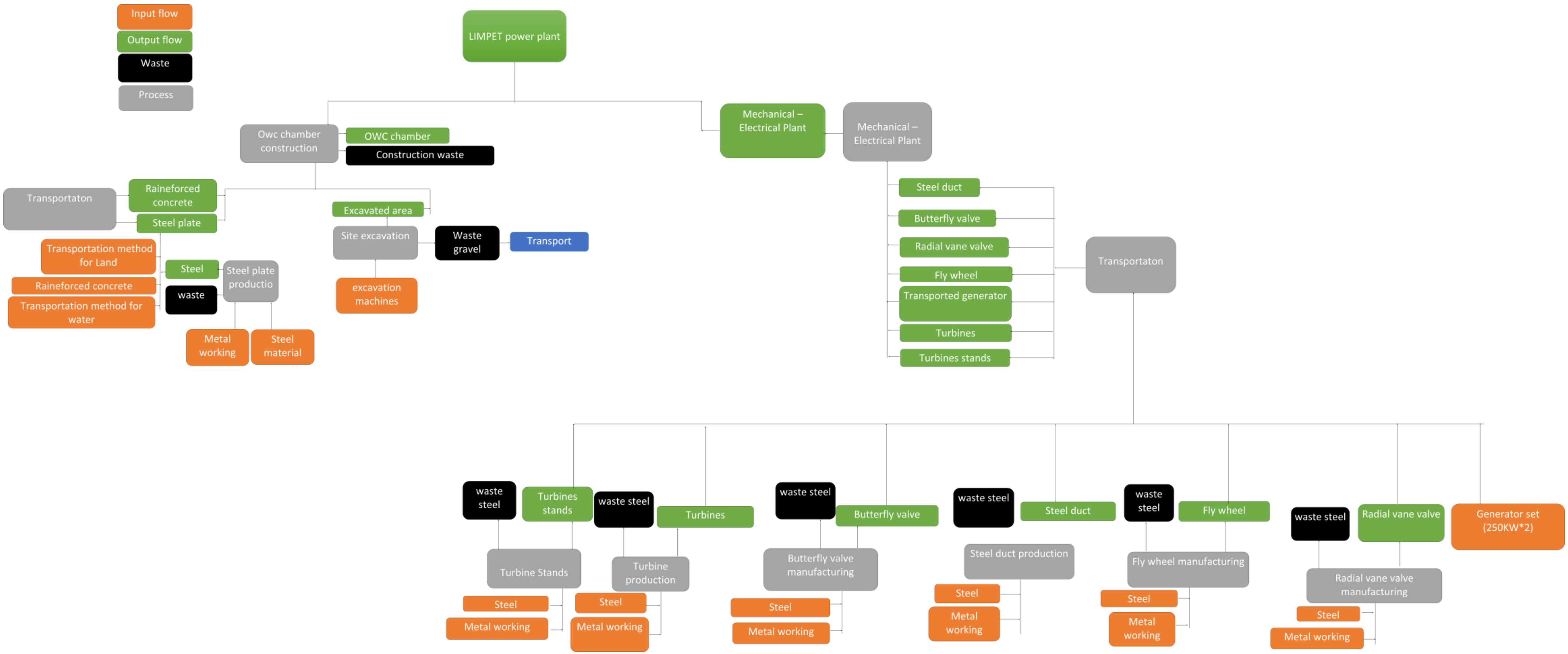


Figure 3.1 The system boundary of the LIMPET plant analysis selected for LCA analysis.

4 LCA inventory analysis

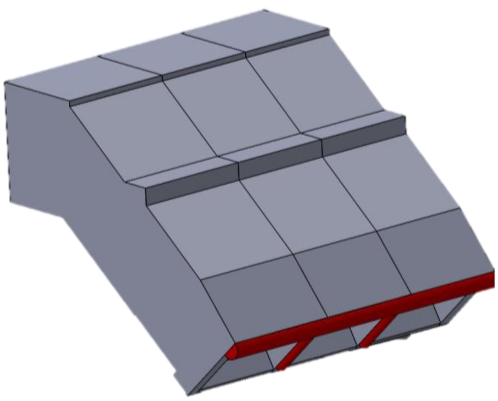
4.1 Overview of the Chapter

In this chapter second phase which is inventory analysis was carried out for the LIMPET plant. Data collection and LCA model creation are discussed. Further assumptions made during this phase were also elaborated.

4.2 Data collection

To analyze the inventory process-based approach was used. Primary data such as plant dimensions, and type of materials used for each part of the plant were taken from the LIMPET project report, and then a 3D model was created on SOLIDWORKS to measure the material quantities. Figures 4.1 to 4.4 show the SOLIDWORKS design and the actual plant component. Dimensions shown in Table 2.1 were taken to model the chamber on SOLIDWORKS. The chamber was constructed using reinforced concrete and the electrical-mechanical plant was manufactured using marine grade steel. But the limitation of the database and lack of data several assumptions were made.

- All the mechanical-electrical plant components were assumed that been transported from Inverness, UK to Islay Island.
- For the land transport method of mechanical-electrical plant components (280 Km) 3.5-7.5 metric ton Lorry was assumed.
- For the water transport method of mechanical-electrical plant components (48 km) bulk carrier was assumed.
- Reinforced concrete was transported distance was assumed 20 Km.
- For all the waste outputs 20% of the material of the component was assumed.



(a)

(b)

Figure 4.1 OWC concrete chamber structure with steel entry-lips and diaphragm walls. (a) SOLIDWORK model, and (b) LIMPET plant.

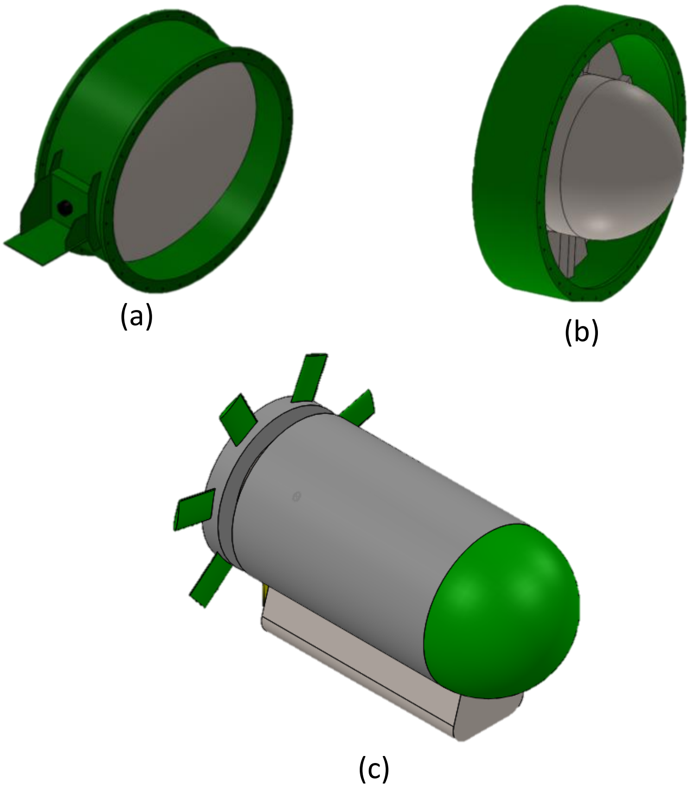
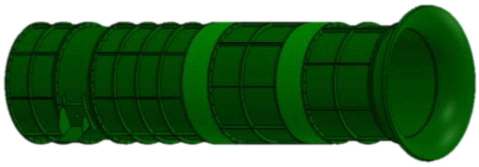


Figure 4.2 SOLIDWORKS model of the (a) butterfly valve, (b) radial vane valve, and (c) Turbine configuration

Figure 4.3 Turbine and duct valves of the LIMPET plant

(a)



(b)

Figure 4.4 Air duct (a) shows the LIMPET plant duct and (b) shows the SOLIDWORK model of the duct.

Using these SOLIDWORKS models, material quantities were calculated as shown in Table 4.1.

Table 4.1 Measured material quantities for different parts of the LIMPET plant.

Name	Quantity	Unit
Reinforced concrete	1026.48	m^3
Steel for entry lip	1876	kg
Steel for Diaphragm Wall	2119	kg
Steel for Diaphragm Wall	2119	kg
Steel for Turbine 1	3180	kg
Steel for Turbine 2	3180	kg
Steel for Radial vane configuration	20200	kg
Steel for Butterfly valve	7820	kg
Steel for Steel duct	26222	Kg
Steel for Turbine 1 stand	17800	kg
Steel for Turbine 2 stand	12530	kg
Steel for Flywheels	5256	kg

Excavation data was taken from the project report as shown in Table 4.2. Further Several assumptions were made because of a lack of data.

- Excavation period was taken as 150 days.
- Transportation of gravel distance was taken as 10 Km.

- For excavation 74.57KW Machine operation was used.

Table 4.2 Excavation process data of the LIMPET plant

Name	Quantity	Unit
Excavation volume	4949	m^3
Waste gravel	4949	m^3
Gravel transport	100	Km

4.3 OpenLCA model preparation

Using OpenLCA software, the LCA model for the LIMPET wave energy converter was created, with processes connected to an existing database. Since relevant geographic data couldn't always be found, assumptions were made. Sometimes it is more practical to adapt high-quality data to another geographical context rather than comparing electricity mixes from different databases but appropriate regions. The Ecoinvent cut-off database was utilized for this purpose.

This approach is common in LCA, especially when specific geographic data isn't available. By using a comprehensive database like Ecoinvent, the model can still be accurate and informative. However, it's crucial to make reasonable assumptions and adjustments to ensure the model reflects the specific context of the study area as closely as possible.

Adapting high-quality data to another geographical context allows for consistency and reliability in the LCA model. This ensures that the results of the LCA are meaningful and can be used to inform decision-making regarding the LIMPET wave energy converter.

Figure 4.5 depicts the excavation process, created using OpenLCA software. In this process, the main input is "machine operation," which represents the operation of excavation machinery. This input is connected to an existing database within OpenLCA, as indicated in the provider section.

The outputs of the excavation process include "excavated site" and "gravel waste."

- The excavated site is a product flow, and it serves as the quantitative reference for this process. It represents the material that has been excavated from the site.
- Gravel waste, on the other hand, is a waste flow generated during the excavation process. This waste material is not utilized directly within the system and is considered waste.

Additionally, the waste gravel is used as an input for gravel transportation, as shown in the provider section. This indicates that the waste gravel generated during excavation is utilized for gravel transportation, potentially for purposes like backfilling and road construction materials.

This process in the product system model (Figure 4.7) is essential for assessing the environmental impacts associated with excavation activities, such as energy consumption, emissions, and waste generation.

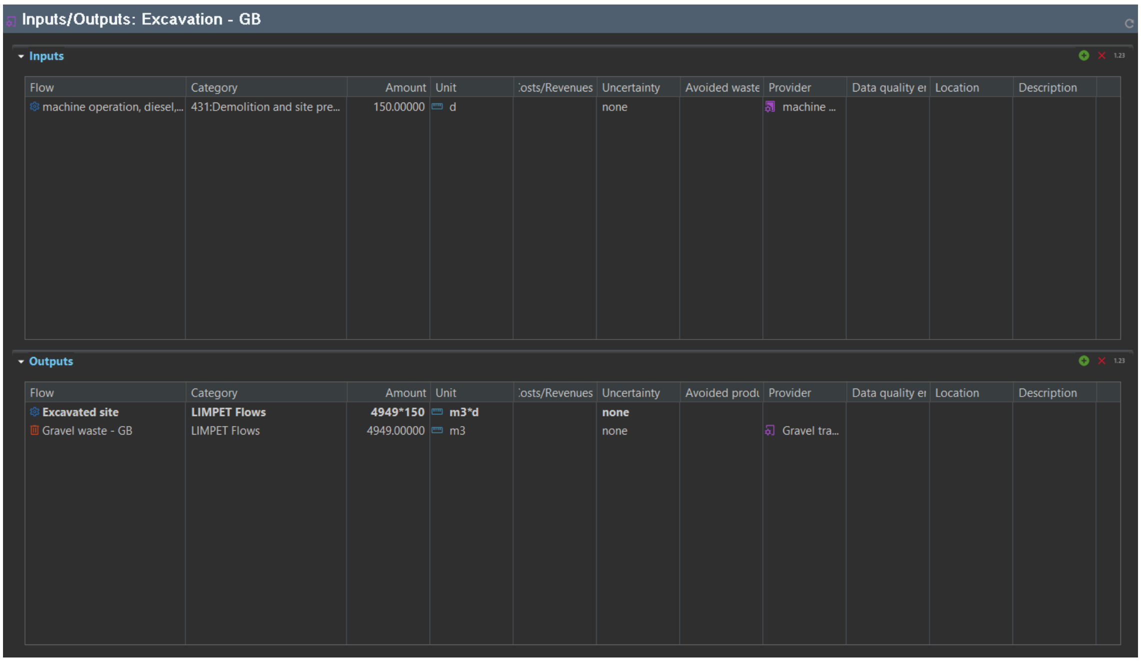


Figure 4.5 Excavation process created on OpenLCA.

Figure 4.6 illustrates the Transportation process for both the Entry lip and Diaphragm walls. In this process, the inputs include "Manufactured Entry lip and Diaphragm Wall," as well as two transportation methods: "transport, freight, lorry 3.5-7.5 metric ton, EURO1" for land transport and "transport, freight, sea, bulk carrier for dry goods" for water transport. These transportation methods are used for land and water, respectively. The outputs of this process are the "Transported Entry lip and Diaphragm Wall."

This process essentially involves moving the manufactured Entry lip and Diaphragm Wall from their manufacturing locations to their destination sites using the specified transportation methods. The products are loaded onto lorries for land transport and bulk carriers for sea transport. Once transported, the Entry lip and Diaphragm Wall are ready for further processes or installation at the construction site.

The purpose of depicting this process in the product system model (Figure 4.7) is to ensure that transportation-related impacts, such as emissions, fuel consumption, and transportation distance, are accounted for in the overall impact assessment of the product system.

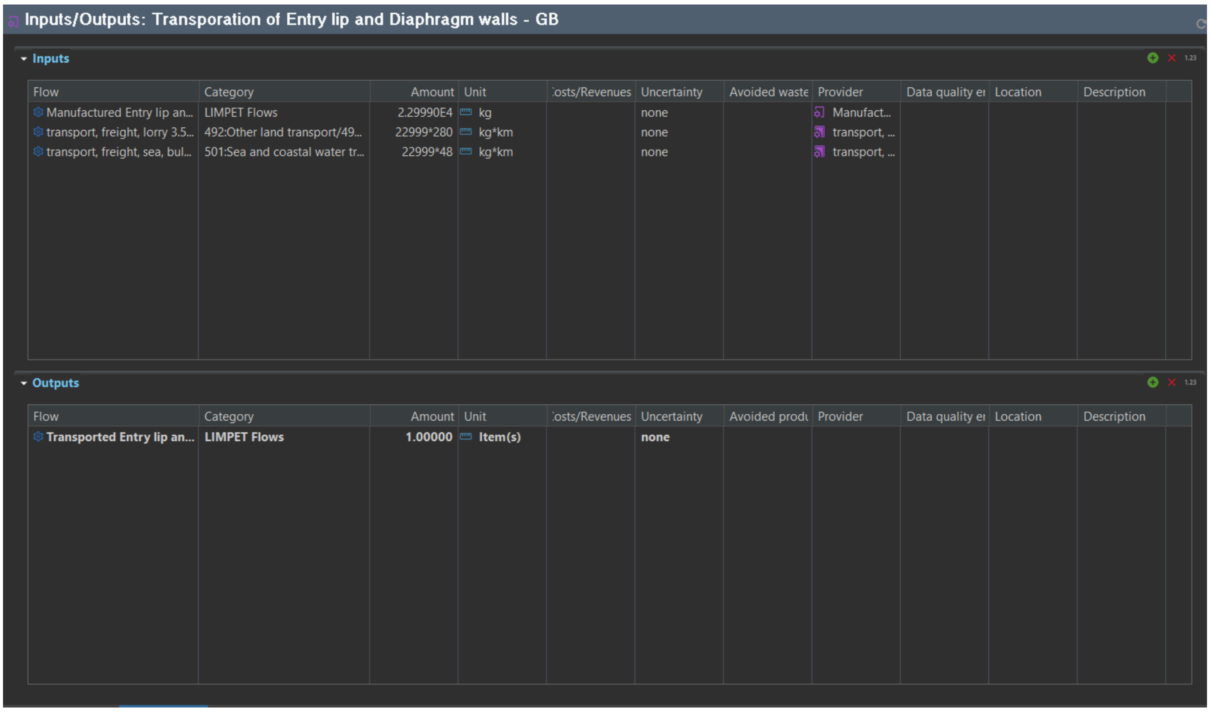


Figure 4.6 Process for transportation of Entry lip and Diaphragm walls

Creating the final model graph of the entire product system involves integrating all the individual unit processes and their interconnections into a comprehensive visualization. This graph provides a clear overview of how each process relates to one another within the system.

Figure 4.7 would be a visual representation of the entire product system, incorporating all the processes outlined in Figure 3.1. Each process is depicted as a node in the graph, with arrows indicating the flow of materials between them.

To make the model graph complete and useful for impact assessment, quantities and relevant units of measurement are added to each process. This ensures that the flow of materials or energy through the system can be accurately represented and quantified.

Once the product system model graph is complete, it serves as the foundation for impact assessment. By understanding how each process contributes to the overall system, the Impact assessment method can calculate the environmental impacts associated with the product throughout its selected life cycle phase (Cradle-to-gate). This could include impacts such as carbon emissions, energy consumption, resource depletion, or other relevant indicators.

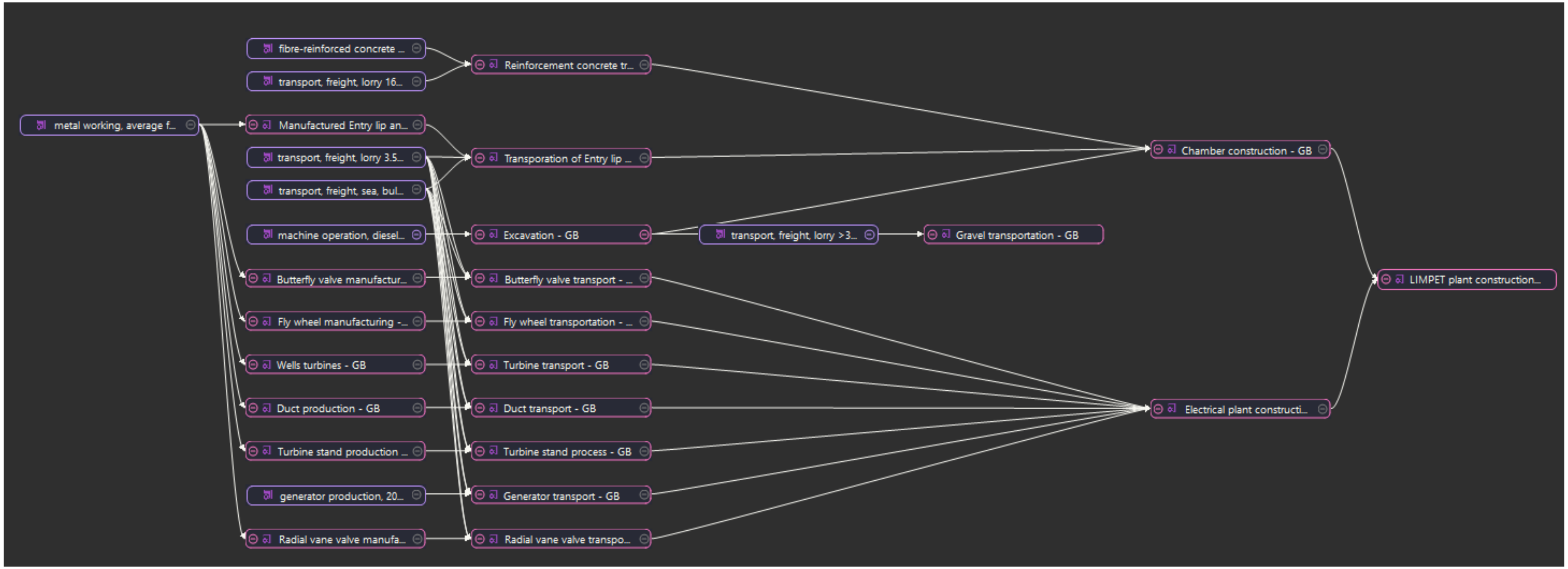


Figure 4.7 Model graph of the product system

5 Impact assessment and interpretation

5.1 Overview of the Chapter

In the impact assessment section of the chapter, various aspects related to the assessment of environmental impacts were discussed. This typically includes Types of Impact Assessment Methods, Impact Categories, and Category Indicators.

More about the impact assessment methods, category categories, and indicators can be found in Chapter 2.

In the interpretation section, the results of the impact analysis are discussed. This typically includes:

1. Discussion of Results:

- Explanation of the environmental impacts identified in the analysis.
- Comparison of impacts across different stages of the life cycle or between alternative scenarios.
- Identification of hotspots or areas of significant impact within the product or process.

2. Sensitivity Analysis

5.2 Impact assessment

For the impact assessment, three methods were used: ReCiPe 2016 Midpoint (H), ReCiPe 2016 Endpoint (H), and EDIP 2003. Both ReCiPe 2016 Midpoint (H) and EDIP 2003 were used compare the midpoint results of selected impact categories which belongs to both methods. Table 5.1 displays the impact categories and their corresponding indicators for each method:

Table 5.1 Impact assessment methods and its impact categories and indicators

Impact method	Impact categories	Category indicator
ReCiPe 2016 Midpoint (H)	Fine particulate matter formation	kg PM2.5 eq
	Fossil resource scarcity	kg oil eq
	Freshwater ecotoxicity	kg 1,4-DCB
	Freshwater eutrophication	kg P eq
	Global warming	kg CO2 eq
	Human carcinogenic toxicity	kg 1,4-DCB
	Human non-carcinogenic toxicity	kg 1,4-DCB

	Ionizing radiation	kBq Co-60 eq
	Land use	m2a crop eq
	Marine ecotoxicity	kg 1,4-DCB
	Marine eutrophication	kg N eq
	Mineral resource scarcity	kg Cu eq
	Ozone formation, Human health	kg NOx eq
	Ozone formation, Terrestrial ecosystems	kg NOx eq
	Stratospheric ozone depletion	kg CFC11 eq
	Terrestrial acidification	kg SO2 eq
	Terrestrial ecotoxicity	kg 1,4-DCB
	Water consumption	m3
ReCiPe 2016 Endpoint (H)	Fine particulate matter formation	DALY
	Fossil resource scarcity	USD2013
	Freshwater ecotoxicity	species. yr
	Freshwater eutrophication	species. yr
	Global warming, Freshwater ecosystem	species. yr
	Global warming, Human health	DALY
	Global warming, Terrestrial ecosystems	species. yr
	Human carcinogenic toxicity	DALY
	Human non-carcinogenic toxicity	DALY
	Ionizing radiation	DALY
	Land use	species. yr
	Marine ecotoxicity	species. yr
	Marine eutrophication	species. yr
	Mineral resource scarcity	USD2013
	Ozone formation, Human health	DALY
	Ozone formation, Terrestrial ecosystems	species. yr

	Stratospheric ozone depletion	DALY
	Terrestrial acidification	species. yr
	Terrestrial ecotoxicity	species. yr
	Water consumption, Aquatic ecosystems	species. yr
	Water consumption, Human health	DALY
	Water consumption, Terrestrial ecosystem	species. yr
EDIP 2003	Acidification	m2
	Aquatic eutrophication EP(N)	kg N
	Aquatic eutrophication EP(P)	kg P
	Bulk waste	kg
	Ecotoxicity soil chronic	m3
	Ecotoxicity water acute	m3
	Ecotoxicity water chronic	m3
	Global warming 100a	kg CO2 eq
	Hazardous waste	kg
	Human toxicity air	person
	Human toxicity soil	m3
	Human toxicity water	m3
	Ozone depletion	kg CFC11 eq
	Ozone formation (Human)	person. ppm. h
	Ozone formation (Vegetation)	m2.ppm.h
	Radioactive waste	kg
	Resources (all)	PR2004
	Slags/ashes	kg
	Terrestrial eutrophication	m2

The following table presents the impact assessment results generated by OpenLCA for each method. ReCipe 2016 (H) provides both Midpoint and Endpoint results, allowing for a comprehensive understanding of impacts across different levels of analysis. On the other hand, EDIP 2013 only presents Midpoint results, offering insights into impacts at an intermediate level of assessment. All the results are given per 500kw OWC plant.

Table 5.2 ReCiPe 2016 Midpoint (H) results

Name	Impact assessment result	Unit per 500kw OWC plant
Fine particulate matter formation	2134.716668	kg PM2.5 eq
Fossil resource scarcity	375236.6933	kg oil eq
Freshwater ecotoxicity	67752.67828	kg 1,4-DCB
Freshwater eutrophication	241.9303111	kg P eq
Global warming	1515762.65	kg CO2 eq
Human carcinogenic toxicity	223266.9221	kg 1,4-DCB
Human non-carcinogenic toxicity	1321696.038	kg 1,4-DCB
Ionizing radiation	33726.40627	kBq Co-60 eq
Land use	116818.2562	m2a crop eq
Marine ecotoxicity	94782.13021	kg 1,4-DCB
Marine eutrophication	85.2800614	kg N eq
Mineral resource scarcity	10656.78831	kg Cu eq
Ozone formation, Human health	5494.23021	kg NOx eq
Ozone formation, Terrestrial ecosystems	5648.49663	kg NOx eq
Stratospheric ozone depletion	0.673796798	kg CFC11 eq
Terrestrial acidification	4513.302574	kg SO2 eq
Terrestrial ecotoxicity	1.33E+07	kg 1,4-DCB
Water consumption	7294.367151	m3

Table 5.3 ReCiPe 2016 Endpoint (H) results

Name	Impact assessment result	Unit
Fine particulate matter formation	1.34178734	DALY
Fossil resource scarcity	140082.444	USD2013
Freshwater ecotoxicity	4.69E-05	species. yr
Freshwater eutrophication	1.62E-04	species. yr
Global warming, Freshwater ecosystems	1.16E-07	species. yr
Global warming, Human health	1.40667457	DALY
Global warming, Terrestrial ecosystems	0.004244448	species. yr
Human carcinogenic toxicity	0.741213702	DALY
Human non-carcinogenic toxicity	0.30136931	DALY
Ionizing radiation	2.86E-04	DALY
Land use	0.001036642	species. yr
Marine ecotoxicity	9.96E-06	species. yr
Marine eutrophication	1.45E-07	species. yr
Mineral resource scarcity	2462.909645	USD2013
Ozone formation, Human health	0.005000003	DALY
Ozone formation, Terrestrial ecosystems	7.29E-04	species. yr
Stratospheric ozone depletion	3.58E-04	DALY
Terrestrial acidification	9.57E-04	species. yr
Terrestrial ecotoxicity	1.52E-04	species. yr
Water consumption, Aquatic ecosystems	4.41E-09	species. yr
Water consumption, Human health	0.016193495	DALY
Water consumption, Terrestrial ecosystem	9.85E-05	species. yr

As depicted in Figure 2.11 in Chapter 2, the endpoint area of protection values in ReCiPe 2016 can be derived by aggregating midpoint categories to damage pathways. Table 5.3 summarizes the endpoint area of protection results, showcasing the aggregated impacts across different damage pathways per 500kw OWC plant.

Table 5.4 ReCiPe 2016 endpoint aggregated results

Endpoint area of protection	Results	Unit
Damage to human health	3.81E+00	DALY
Damage to ecosystems	7.44E-03	species. yr
Damage to resource availability	142545.4	USD2013

Table 5.5 displays the results obtained using the EDIP 2003 method. It is valuable to compare the impact of the LIMPET plant across different impact categories, especially those not included in ReCiPe methods, such as Bulk waste, Radioactive waste, and others. This comparison offers insights into the broader environmental implications of the LIMPET plant beyond the impact categories covered by ReCiPe methods.

Table 5.5 EDIP 2003 results

Name	Impact assessment result	Unit per 500kw OWC plant
Acidification	89783.9002	m2
Aquatic eutrophication EP(N)	662.1435915	kg N
Aquatic eutrophication EP(P)	213.0395615	kg P
Bulk waste	1676579.003	kg
Ecotoxicity soil chronic	4.37E+07	m3
Ecotoxicity water acute	6.11E+08	m3
Ecotoxicity water chronic	3.77E+09	m3
Global warming 100a	1487172.941	kg CO2 eq
Hazardous waste	44.39503564	kg
Human toxicity air	7.81E+10	person
Human toxicity soil	914840.2899	m3
Human toxicity water	1.42E+08	m3
Ozone depletion	0.127478689	kg CFC11 eq
Ozone formation (Human)	814.5083036	person. ppm. h
Ozone formation (Vegetation)	1.17E+07	m2.ppm.h
Radioactive waste	94.31768449	kg
Resources (all)	377.9862374	PR2004
Slags/ashes	3023.680449	kg
Terrestrial eutrophication	142058.97	m2

It is observed that the Global warming value of both ReCiPe 2016(H) Midpoint and EDIP 2003 give nearly the same results giving 1515762.65 Kg CO_2 eq and 1487172.941 respectively. There is a 28589.709 Kg CO_2eq. Ozone depletion has a difference of 0.546318109 Kg CFC11 eq. apart from that there are unique impact categories.

5.3 Interpretation

5.3.1 ReCipe 2016 Midpoint (H) results

The results of the selected impact categories and their main contributing processes to the impact category were discussed. The rest of the impact categories are included in Appendix I.

Figure 5.1 shows the Sankey diagram of the Fine particulate matter formation of the ReCiPe 2016 Midpoint (H). 72.41% of the impact was contributed by the chamber construction. This could be due to activities such as concrete mixing, drilling, and other construction-related operations that generate dust and particulate emissions. When looking at the upstream flows of the chamber construction, the excavation process has the highest impact among the upstream processes, which is 37.897%. Excavation involves activities such as digging, earthmoving, and transportation of gravel, which can release dust and particulate matter into the air, contributing to fine particulate matter formation.

Understanding these contributions helps identify areas where improvements or mitigation measures could be implemented to reduce the environmental impact of the chamber construction process, particularly focusing on controlling dust emissions during excavation activities.

Fine particulate matter formation from the electrical-mechanical plant accounts for 27.59% of the impact, mainly due to the manufacturing of steel components and the transportation of those components to the installation site.

The manufacturing process for steel components involves various operations such as cutting, shaping, and welding, which can release particulate matter into the air when creating components for the plant such as turbines, flywheels, generators, ducts, etc. This is significant for processes like welding, where fine metal particles and other contaminants can be generated.

The transportation of steel components involves the use of vehicles, which emit particulate matter and other pollutants from combustion engines. Dust and particulate matter may also be generated during loading, unloading, and handling of components during transit.

The significant contribution of these processes to fine particulate matter formation highlights the importance of implementing measures to reduce emissions and control dust throughout the manufacturing and transportation processes. This could include implementing cleaner production technologies, optimizing transportation routes, and using pollution control devices to mitigate environmental impacts.

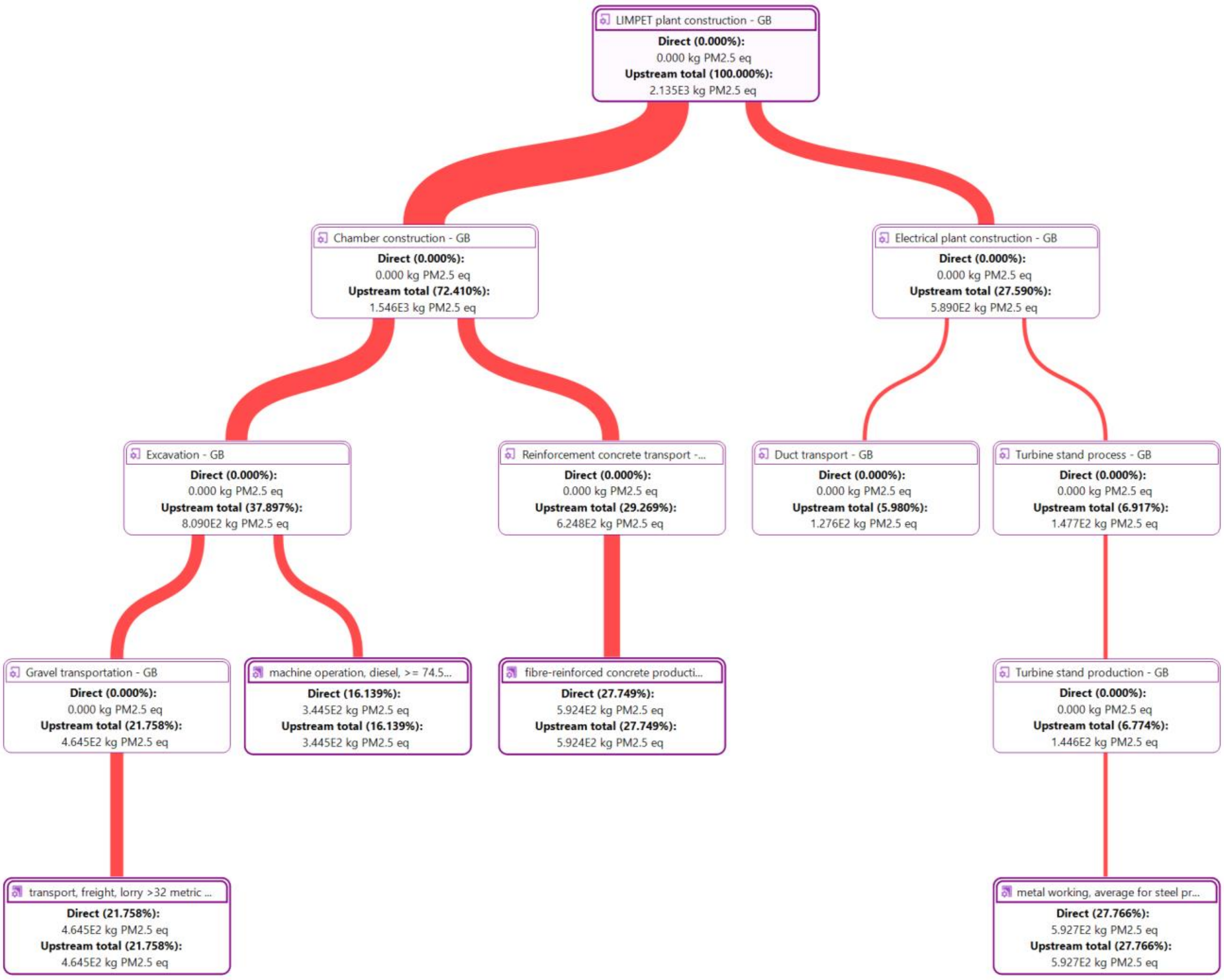


Figure 5.1 Fine particulate matter formation

Figure 5.2 shows the Sankey diagram of fossil resource scarcity. 80.42% of the impact comes from chamber construction, 54.1% from excavation and 22.032% from the transport of reinforced concrete. Excavation contributes significantly to fossil resource scarcity due to the energy-intensive nature of earthmoving machinery and the use of fossil fuels in transportation. Transporting reinforced concrete to the construction site also contributes to fossil resource scarcity, mainly due to the energy required for vehicles.

The remaining 19.58% of the impact comes from the electrical and mechanical plant, which is then subdivided into other unit processes of the electrical-mechanical plant.

The electrical and mechanical plant contributes to fossil resource scarcity through various processes involved in manufacturing steel components and transporting them to the installation site.

These processes may include the production of turbines, flywheels, ducts, valves, and turbine stands, each requiring fossil fuels for manufacturing and transportation.

Understanding the significant contributions of these processes to fossil resource scarcity allows for targeted efforts to reduce the environmental impact. For example, improving the efficiency of excavation machinery, optimizing transportation routes, and using alternative materials or renewable energy sources can help mitigate fossil resource depletion associated with chamber construction and electrical-mechanical plant manufacturing.

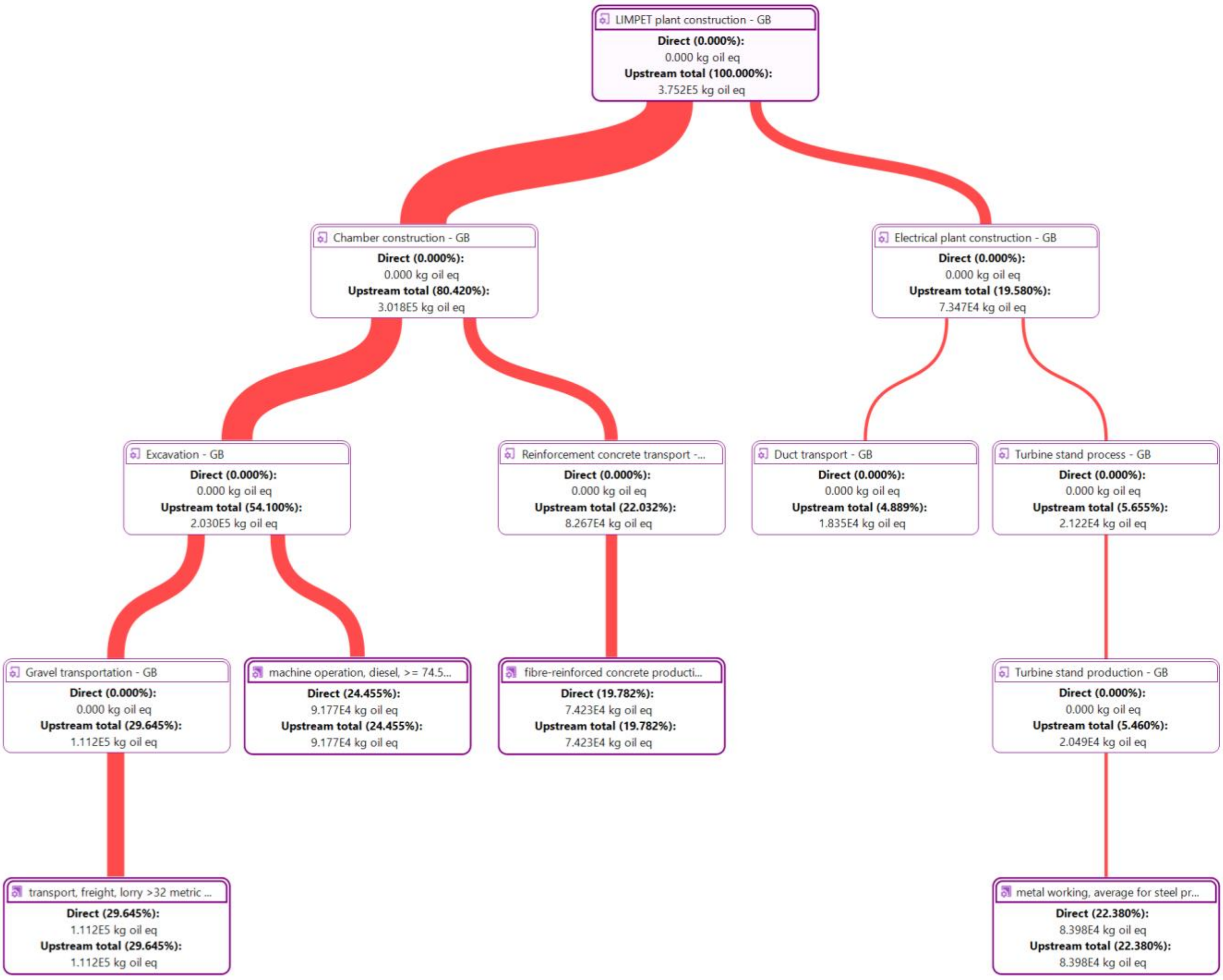


Figure 5.2 Fossil resource scarcity

In Figure 5.3, the Global warming impact is depicted, where more than four-fifths of the impact (81.587%) comes from chamber construction. This includes activities such as waste gravel transport, excavation machine operation, and reinforced concrete production. These processes emit greenhouse gases primarily through energy use and transportation. For example, excavation machine operation relies on fossil fuels, and transportation of materials emits CO_2 from vehicle exhaust.

The electrical-mechanical plant contributes 18.413% to the global warming impact. This is mainly due to greenhouse gas emissions from manufacturing processes and transportation associated with the plant's components. Manufacturing of steel components and other plant materials requires energy, often derived from fossil fuels, leading to CO_2 emissions. Further, the transportation of these components to the installation site adds to the emissions footprint.

To mitigate these impacts, emissions from both construction and operational phases should be reduced. Energy-efficient construction and manufacturing practices can minimize the use of fossil fuels and reduce emissions. Optimizing transportation routes to minimize distance and using cleaner fuels for vehicles can also help lower the carbon footprint. Transitioning to renewable energy sources for both construction and operation can further reduce greenhouse gas emissions associated with the LIMPET plant.

By implementing these strategies, the LIMPET plant could have significantly reduced its contribution to global warming and mitigated its environmental impact.

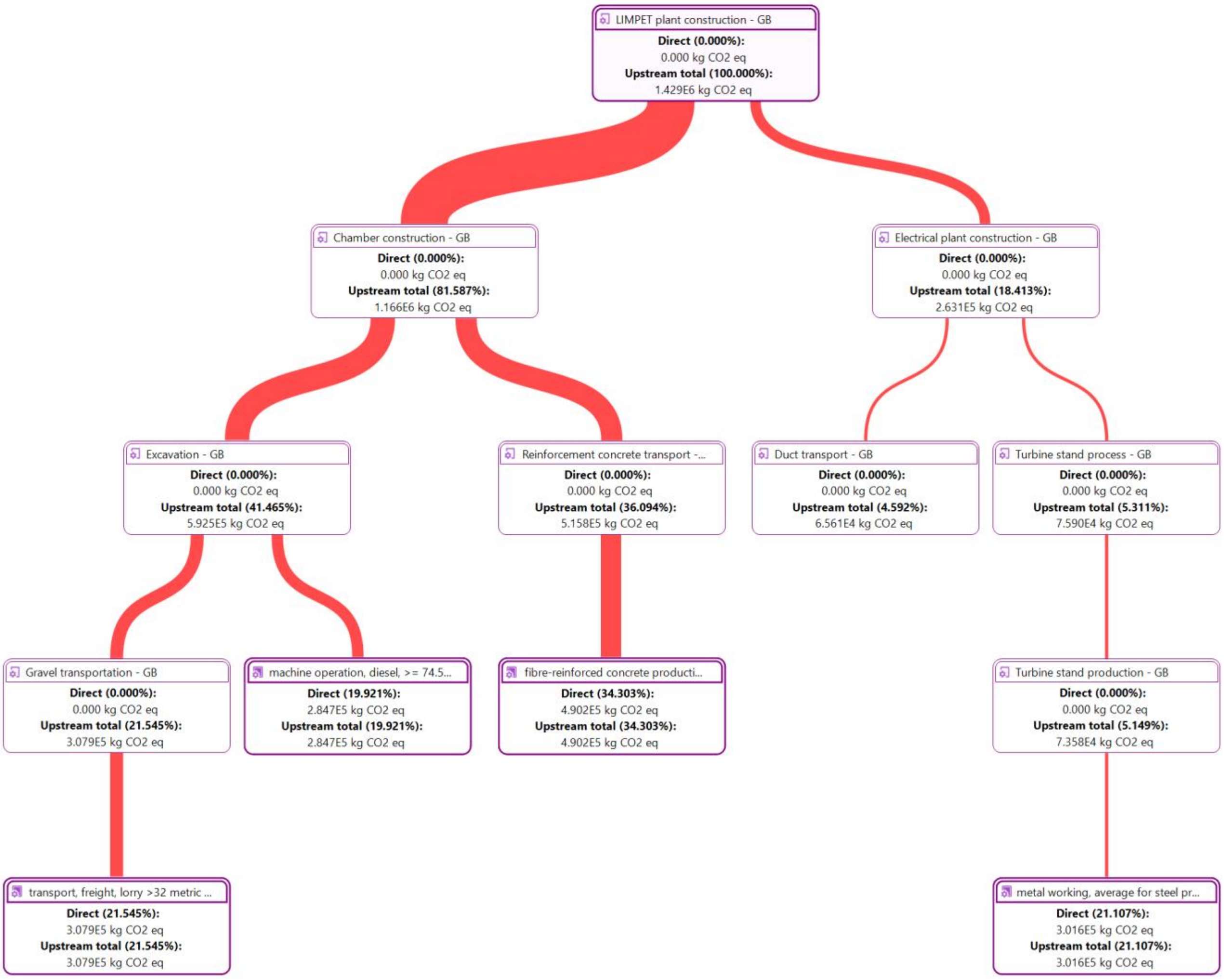


Figure 5.3 Global warming

Figure 5.4 illustrates the land use impact category, where chamber construction accounts for the vast majority of the impact (94.592%), with the remaining 5.408% attributed to the electrical-mechanical plant. Surprisingly, the generator manufacturing process shows a positive impact on the environment. However, this may be misleading due to the selection of elementary flows from the database that underestimate the actual impact.

Chamber construction activities, such as excavation, site preparation, and concrete pouring, have significant implications for land use. These processes often involve clearing natural habitats, disrupting ecosystems, and altering landscapes, leading to land degradation and loss of biodiversity. The extensive land disturbance associated with chamber construction contributes substantially to the overall land use impact.

The electrical-mechanical plant contributes to land use impact primarily through its manufacturing processes and transportation activities. Manufacturing facilities and infrastructure require land for operation, and transportation of components may further contribute to habitat fragmentation and resource extraction. While this contribution is smaller compared to chamber construction, it still has notable implications for land use.

Although the generator manufacturing process shows a positive impact on land use, it's important to note that this may be misleading. The selected process from the database contains elementary flows like “Transformation, to wetland, inland (non-use)”, “Transformation, to forest, secondary (non-use)”, “Transformation, to grassland, natural (non-use)”, “Transformation, to shrub land, sclerophyllous”, and “Occupation, dump site”, which assigned a negative CF on land use. This means that the positive impact shown may be an underestimation due to those flows.

In summary, the significant land use impact from chamber construction underscores the importance of minimizing environmental disruption during construction activities. Meanwhile, the positive impact of the generator manufacturing process should be interpreted cautiously, considering the potential underestimation caused by excluding certain land use flows with negative CF. It's crucial to accurately assess all impacts to inform decision-making and ensure effective environmental management strategies.

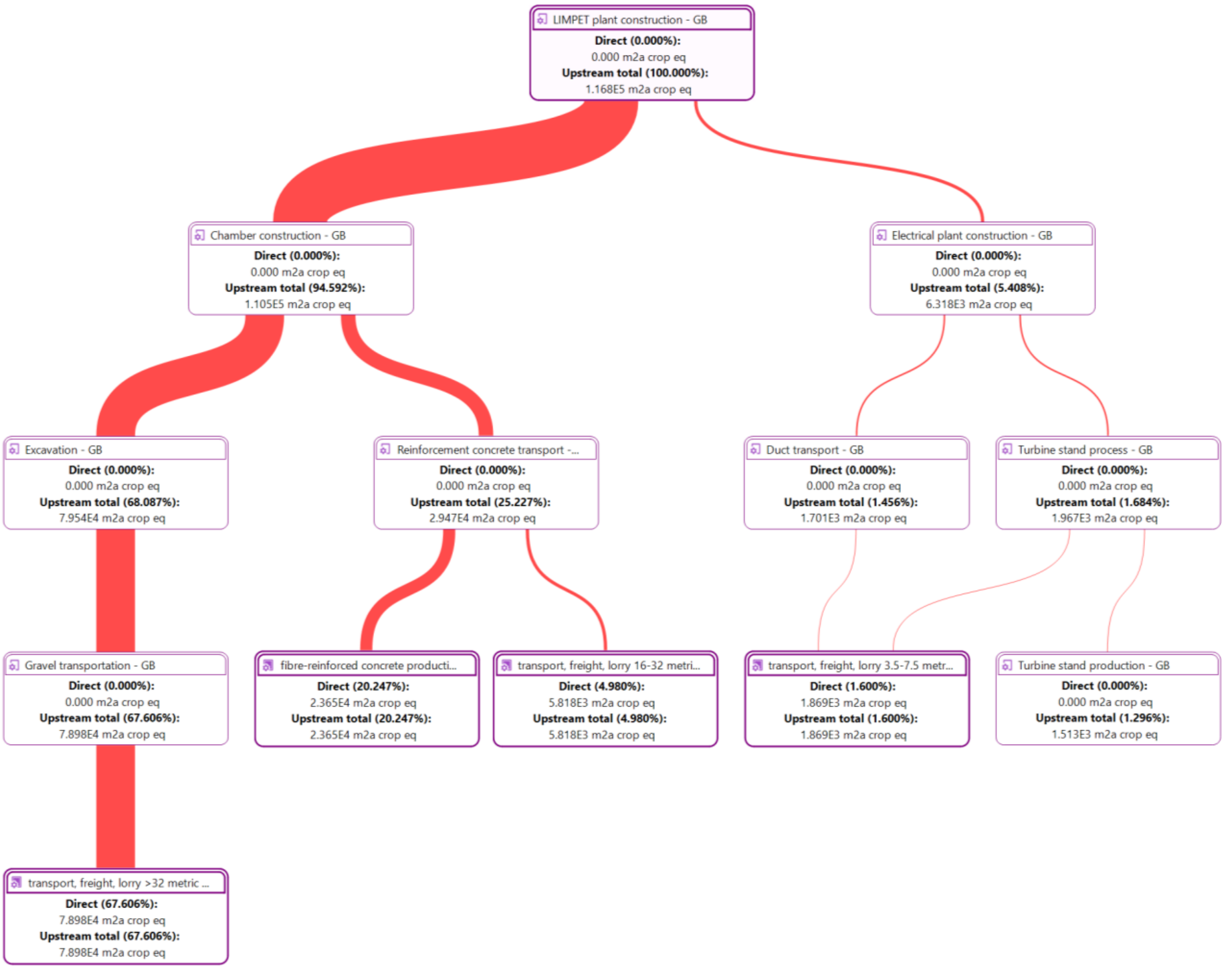


Figure 5.4 Land use

Figure 5.5 illustrates the Marine ecotoxicity impact from the LIMPET plant. Of this impact, 47.691% is attributed to the chamber construction phase, while the remaining 52.309% is attributed to the electrical-mechanical plant.

Nearly half of the Marine ecotoxicity impact comes from chamber construction activities. These activities may involve the use of materials and chemicals that can leach into water bodies during construction, such as concrete production and excavation, contributing to marine pollution and ecotoxicity.

The electrical-mechanical plant contributes slightly more than half of the Marine ecotoxicity impact. This impact is likely from manufacturing processes and transportation of the plant's components. Chemicals and pollutants used or released during manufacturing and transportation can also contribute to marine pollution and ecotoxicity.

This distribution of impact between chamber construction and the electrical-mechanical plant emphasizes the importance of considering environmental impacts. Strategies like pollution prevention measures, using fewer toxic materials, and ensuring proper disposal of waste materials can be conducted to minimize the release of harmful substances into marine environments.

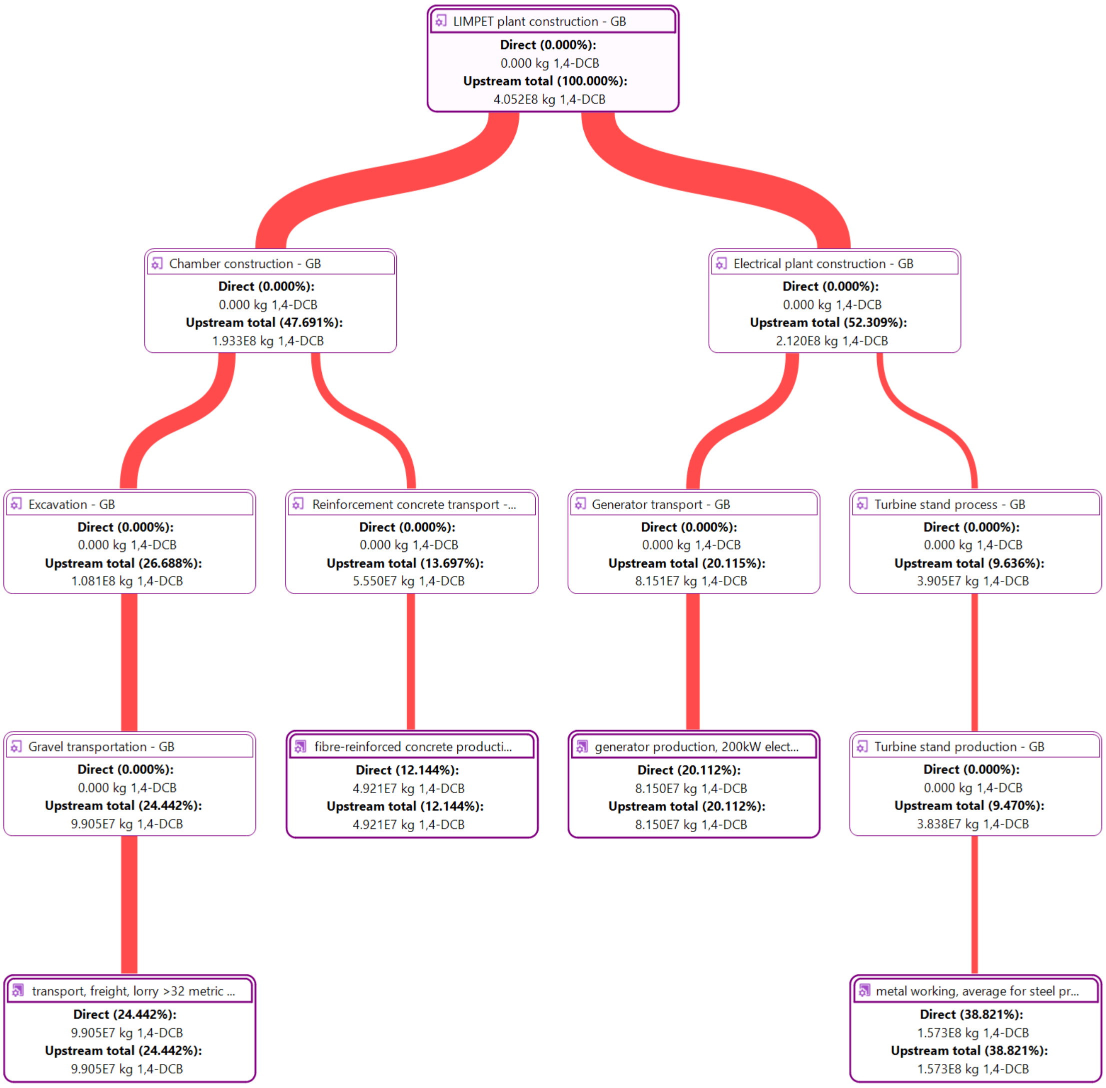


Figure 5.5 Marine ecotoxicity

Figure 5.6 illustrates how Marine eutrophication occurred during the building of the plant. It shows that 63.102% of the impact occurred from the chamber construction. The remaining 36.898% of the impact occurred from the electrical-mechanical plant.

Most of the Marine eutrophication impact is attributed to chamber construction. This impact may occur activities such as excavation, concrete pouring, and site preparation. These can lead to nutrient runoff and sedimentation in marine ecosystems, contributing to eutrophication.

The electrical-mechanical plant contributes to Marine eutrophication impact. This impact may result from manufacturing processes and transportation associated with the plant's components.

The significant contribution from chamber construction to Marine eutrophication underscores the importance of implementing measures to mitigate nutrient runoff and sedimentation during construction activities. Best practices such as erosion control, sediment management, and minimizing the use of chemicals can help reduce the impact.

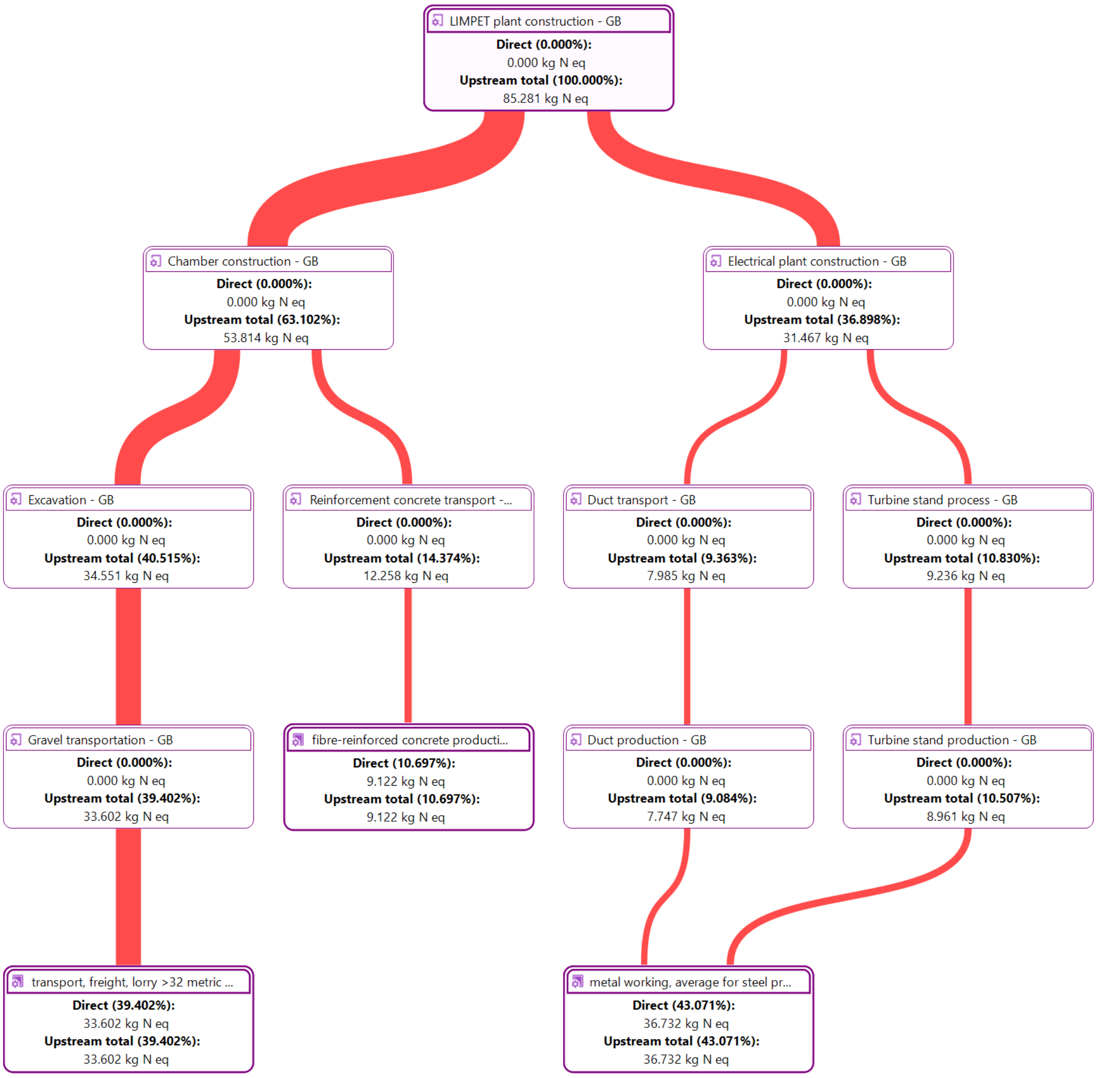


Figure 5.6 Marine eutrophication

Figure 5.7 depicts the Mineral resource scarcity impact. Of this impact, 57.667% was allocated to chamber construction, while the remaining 42.333% was accounted for by the electrical-mechanical plant.

Most of the Mineral resource scarcity impact is attributed to chamber construction. Extraction and consumption of minerals and resources during construction activities such as excavation, concrete production, and site preparation may lead to the impact. These processes require significant amounts of materials, including aggregates, cement, and metals, which can deplete mineral resources.

The electrical-mechanical plant impact is likely from the manufacturing processes and transportation associated with the plant's components, which require materials and resources such as metals, plastics, and rare earth elements.

The significant contribution from chamber construction to Mineral resource scarcity underscores the importance of implementing sustainable construction practices and minimizing resource consumption. Strategies such as using recycled materials, optimizing material usage, and adopting circular economy principles can help reduce the mineral resource scarcity.

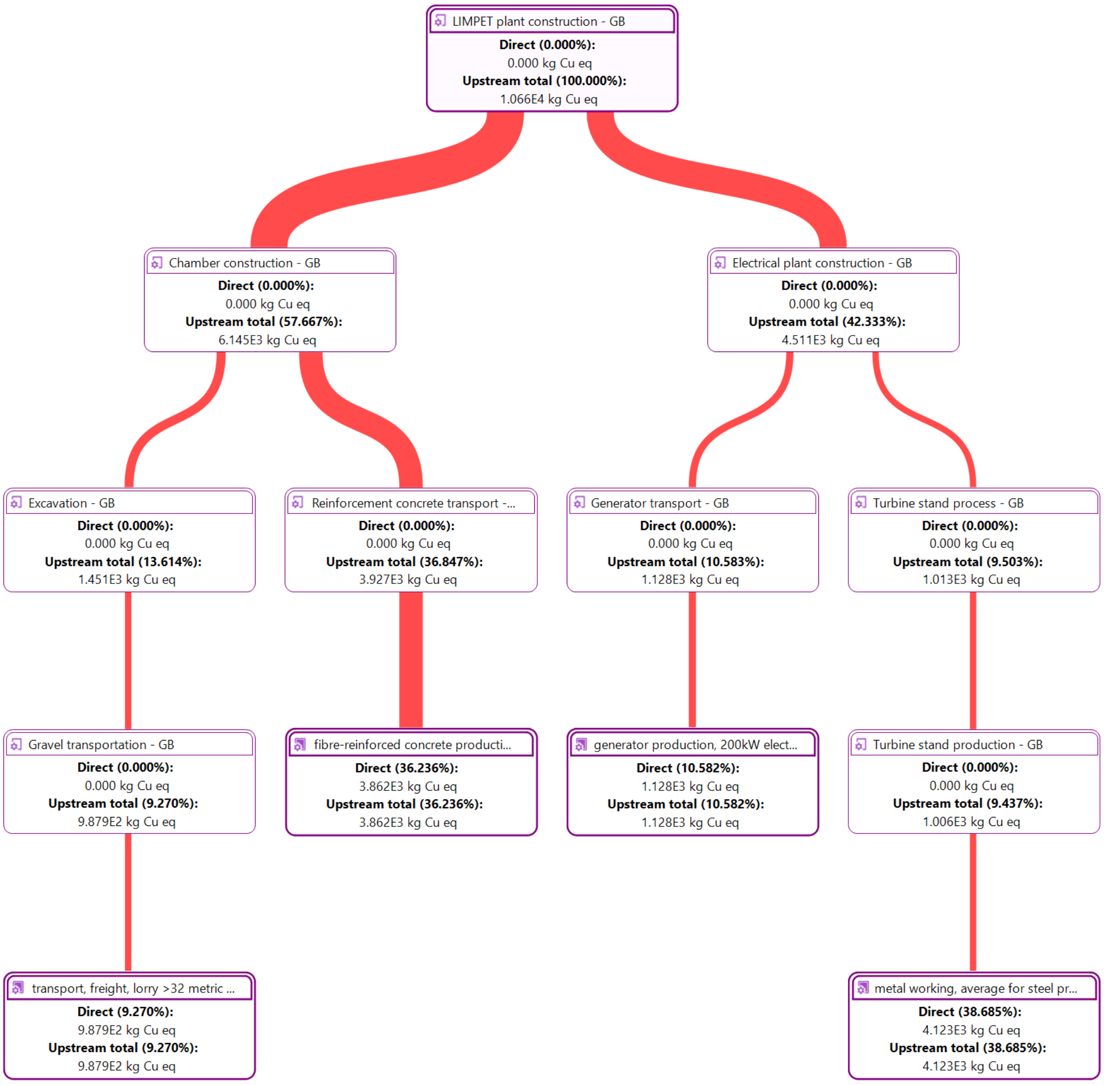


Figure 5.7 Mineral resource scarcity

5.3.2 Sensitivity analysis.

Since material waste was not given. 20% excess material from the material which a particular process requires is considered as waste as an assumption when assessing the impact. To avoid the possible errors that occur due to that assumption sensitivity analysis is done by varying the waste amount as 25% and 30%. Below radar graph below shows the results of impact categories of the ReCiPe 2016 Midpoint (H).

The radar graph shows the relative indicator results of each project variant. For each indicator, the maximum result is set to 100% and the results of the other variants are displayed as this result.

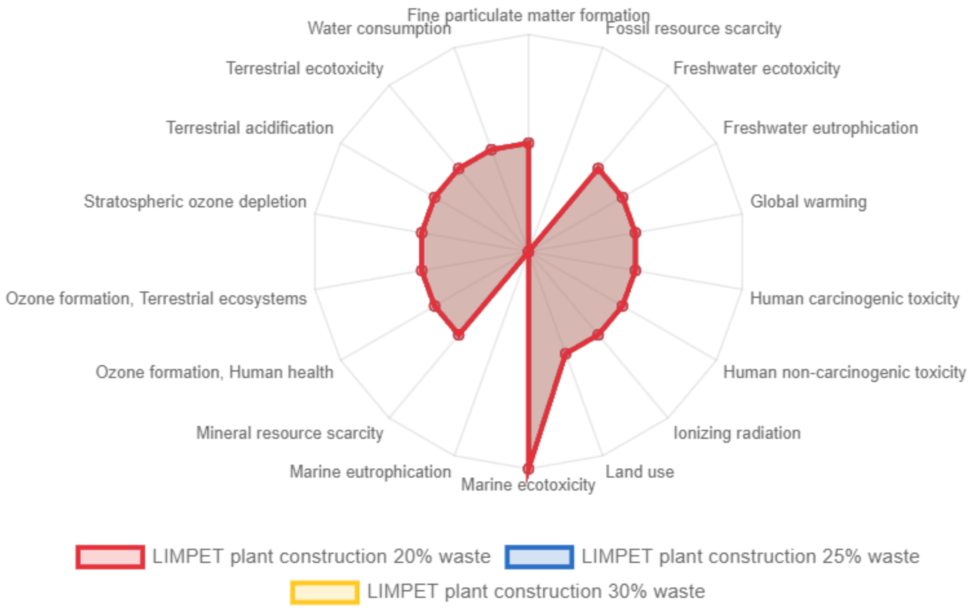


Figure 5.8 Radar graph of the sensitivity analysis

As illustrated in the above figure, it is observed that the differences among the different waste quantities are minimal. All three scenarios show nearly identical results across various impact categories.

This suggests that the environmental impact is not significantly sensitive to changes in the waste percentage assumption within the given range (20%, 25%, and 30%). It implies that the chosen waste assumption of 20% may adequately represent the actual environmental impact associated with material waste for the LIMPET plant.

While sensitivity analysis is valuable for understanding potential variations in impact assessments, in this case, the impact categories seem robust to changes in the waste percentage. This consistency indicates that the chosen waste assumption is reasonable and provides reliable results for environmental impact assessment.

5.4 Carbon and energy payback times.

The carbon and energy payback periods are major aspects when assessing the quality of renewable energy. The carbon payback period gives the period of compensating for carbon emitted during the life cycle of the converter by carbon emissions savings caused by using renewable energy sources carbon emitted during the life cycle of the converter. When it comes to the energy payback period it also gives the period of compensating energy used for the construction of energy by the energy generation. These two can be calculated by the below equations.

$$CO_2eq\ payback\ period = \frac{Total\ CO_2eq\ emmisions\ during\ the\ life\ cycle}{Annuel\ CO_2eq\ avoided} \tag{5.1}$$

$$Energy\ payback\ time = \frac{Energy\ spent\ during\ the\ life\ cycle}{Annual\ energy\ produced} \tag{5.2}$$

LIMPET's total emissions of CO_2eq are 1515762.65 $kg\ CO_2eq$. Considering then that the UK residual grid mix has a carbon intensity of average 400 $kg\ CO_2eq\ /kWh$ in 2009 [20], and that the total annual energy production in 2001 was 27081 kWh. Because of maintenance and failures, the plant was not operated for 4905.8 hours in 2001 year giving low electricity generation [9], the CO_2 payback time is 0.14 years.

Approximating the total energy spent during the LIMPET life cycle with the result obtained from the “Fossil resource scarcity” impact category, the value to be considered is 375236.6933 kg oil eq, which corresponds to 4364002.743079 kWh. Considering then the value of annual energy production stated before, the energy payback time amounts to 161.15 years. Operating hour loss and low efficiency lead to a large period to pay back the energy.

6 Conclusion and Future Works

The Life Cycle Assessment (LCA) analysis of the LIMPET 500 kW oscillating water column (OWC) plant, which was in operation until 2011, faced a lot challenges in terms of efficiency and reliability. These challenges resulted in lower energy production than expected. Hence, it leads to a substantial energy payback period of 161.15 years.

Despite the lengthy energy payback period, the carbon payback period for the LIMPET plant was significantly shorter giving 0.14 years of payback period time. This shorter carbon payback period is attributed to the high carbon intensity of the conventional energy mix during the plant's operational period, which was around 400 kg CO_2e/kWh in 2009. By replacing traditional energy sources with the LIMPET plant, a considerable reduction in carbon emissions was achieved. Improving the plant's efficiency and reducing its operational failures would have further environmental benefits. Enhanced performance would decrease both the energy and carbon payback periods, making the plant more sustainable and environmentally friendly.

According to the literature, when compared to onshore wave energy converters (WECs), the offshore and near-shore WECs' environmental impact was higher. Onshore WECs tend to be more environmentally friendly. Because the installation and maintenance of offshore and near-shore power plants require extensive use of marine vessels. These marine operations contribute significantly to the overall environmental footprint.

Another critical aspect highlighted by the analysis is the importance of material selection and construction methods in minimizing environmental impacts. Using reliable, recyclable materials and adopting sustainable construction practices can significantly reduce the lifecycle environmental footprint of wave energy projects.

In summary, the LIMPET 500 kW OWC plant's LCA analysis showcases the critical role of operational efficiency, reliability, and strategic material selection in enhancing the sustainability of wave energy converters. Improving these factors can lead to substantial reductions in both energy and carbon payback periods, contributing to a more sustainable and environmentally friendly energy solution.

6.1 Future works

In terms of LCA analysis, to reduce the overestimation and underestimation of the environmental impact caused by assumption and the data quality problems, a full cradle-to-grave LCA analysis should be performed on an OWC WEC. Further, conduct a comparative analysis with other ocean WEC to identify the most impact full wave energy harnessing method. In terms of the WECs to reduce the environmental impact efficiency should be increased and proper materials and construction methods should be used to reduce the impact.

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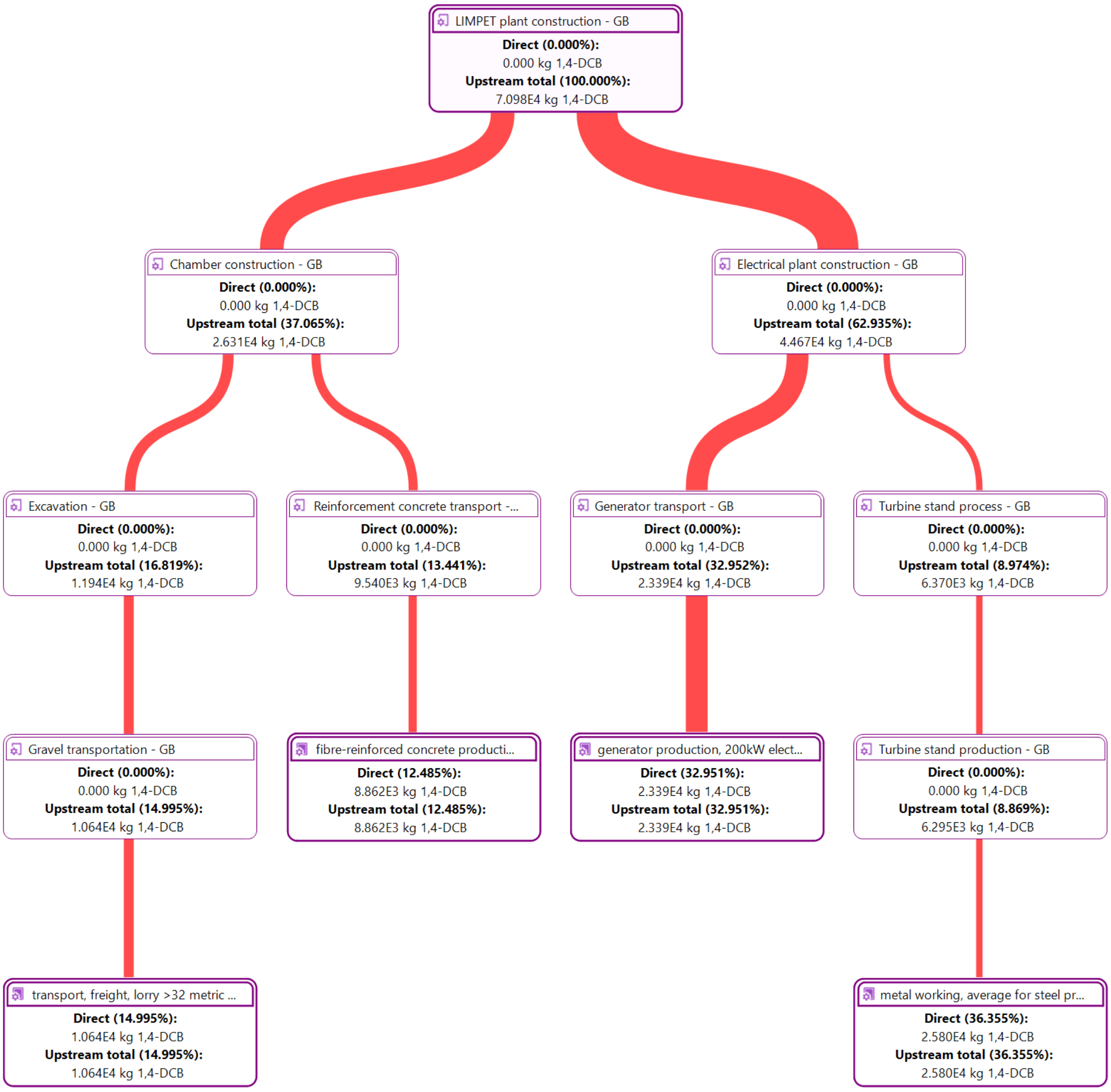
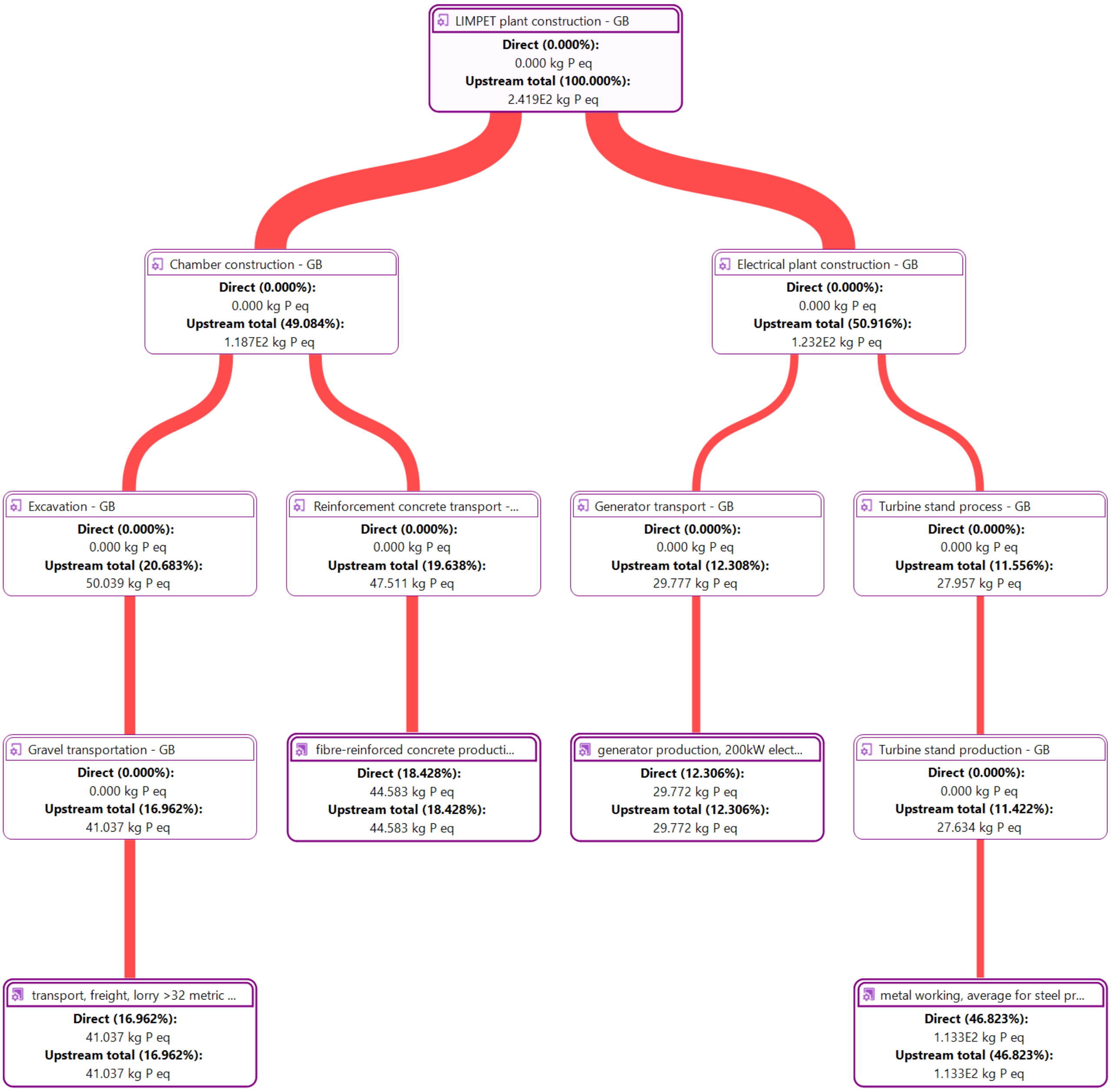
Appendices

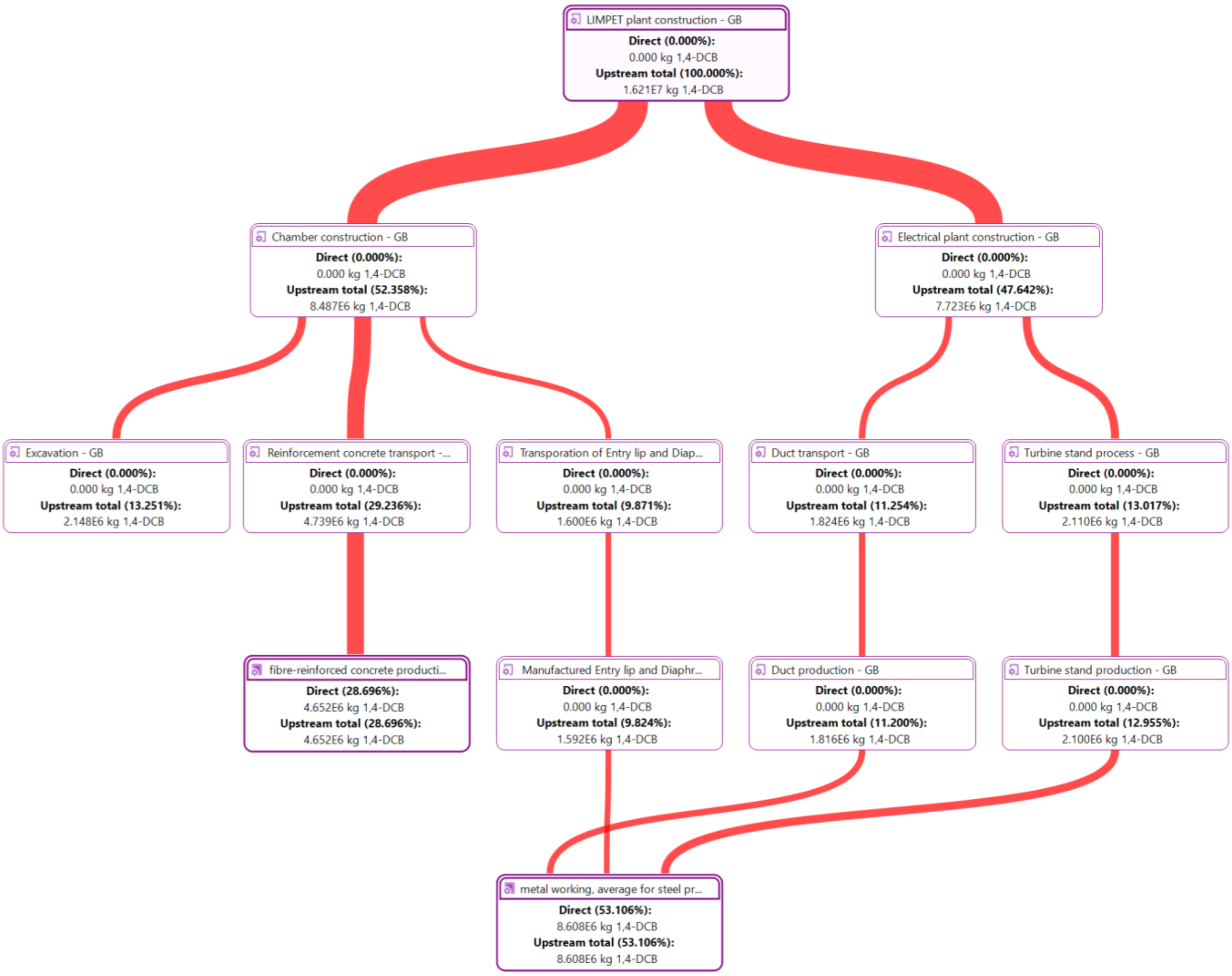
Appendix A ReCiPe 2016 (H) Midpoint impact categories.



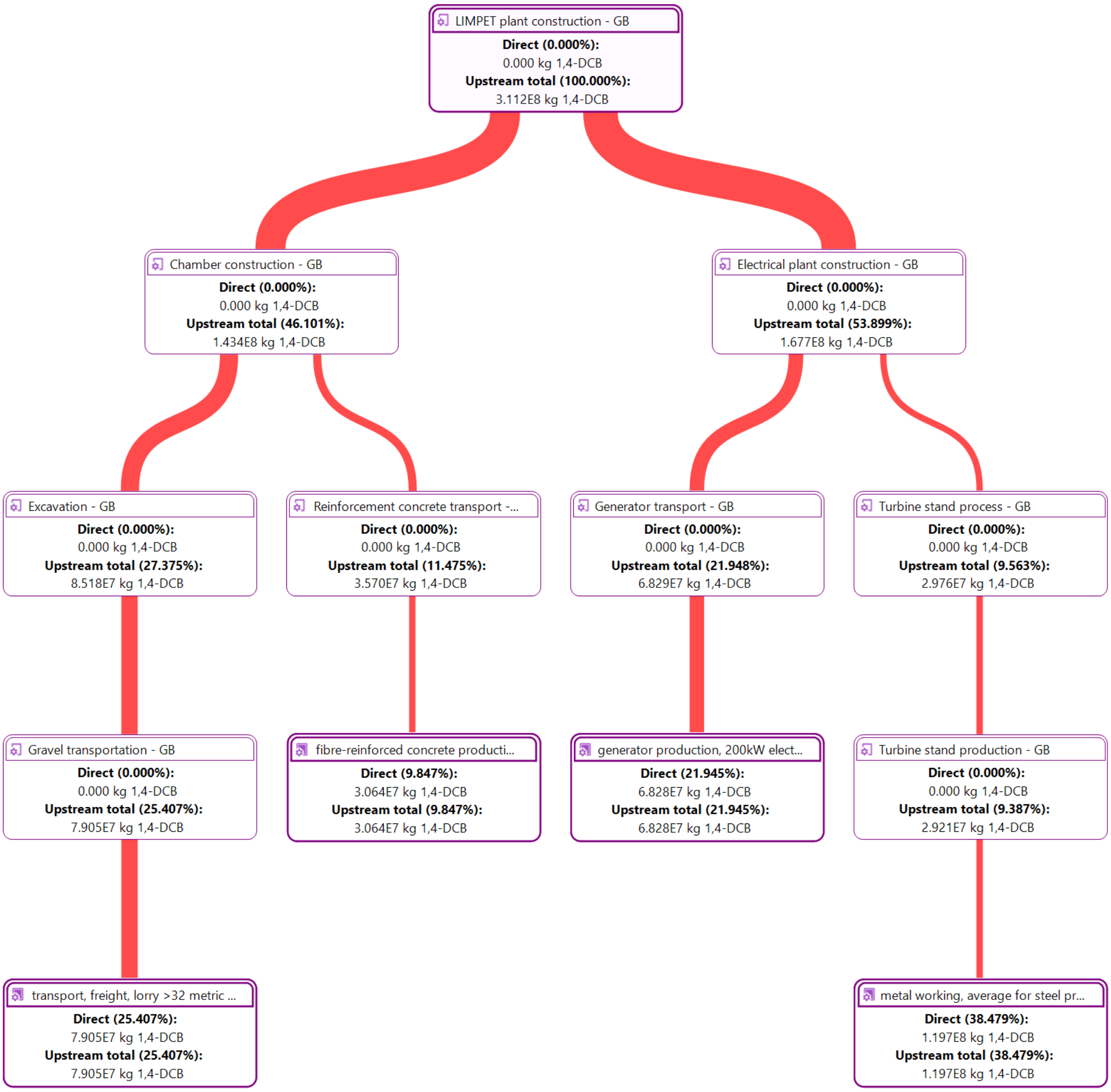
Freshwater ecotoxicity



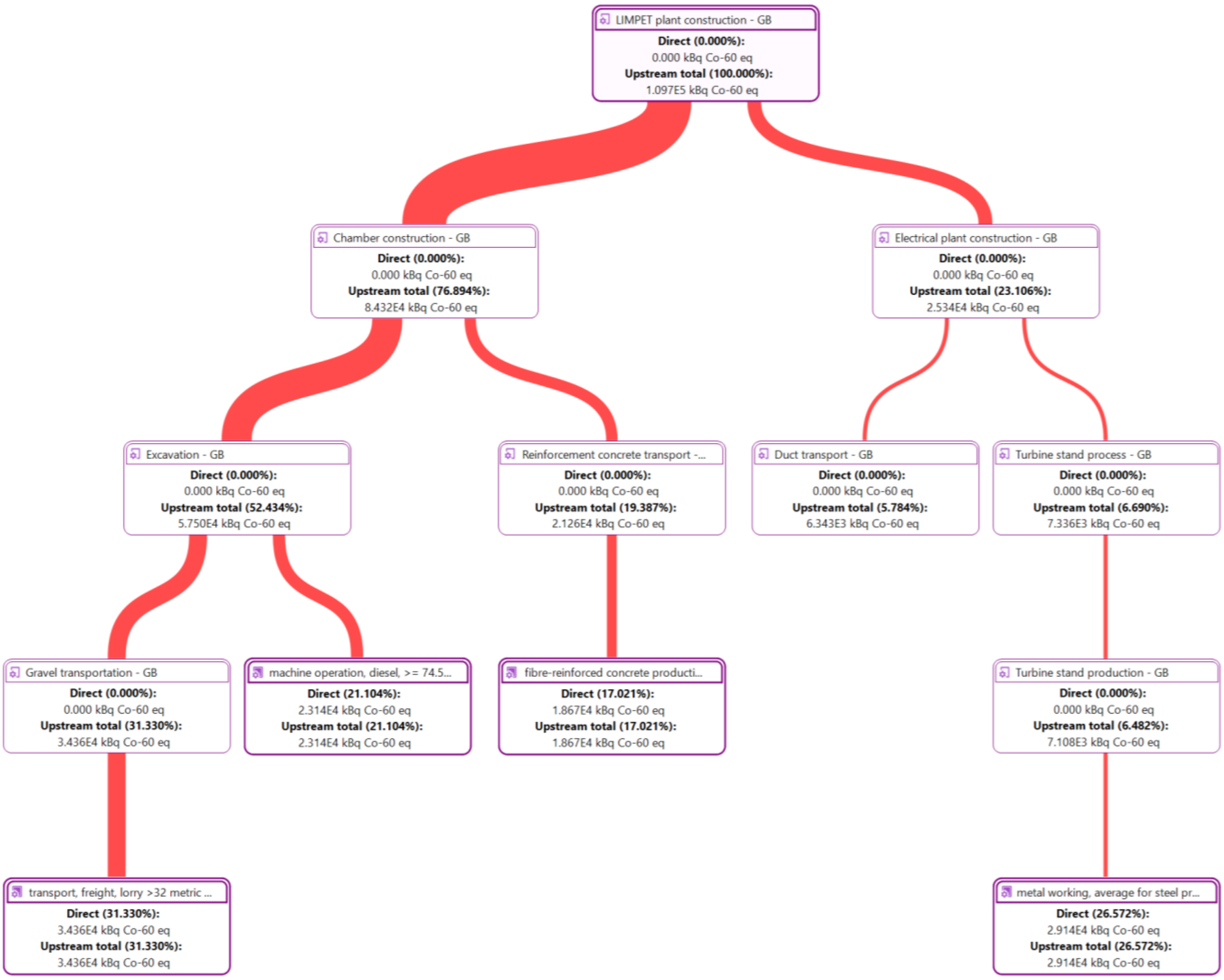
Freshwater eutrophication



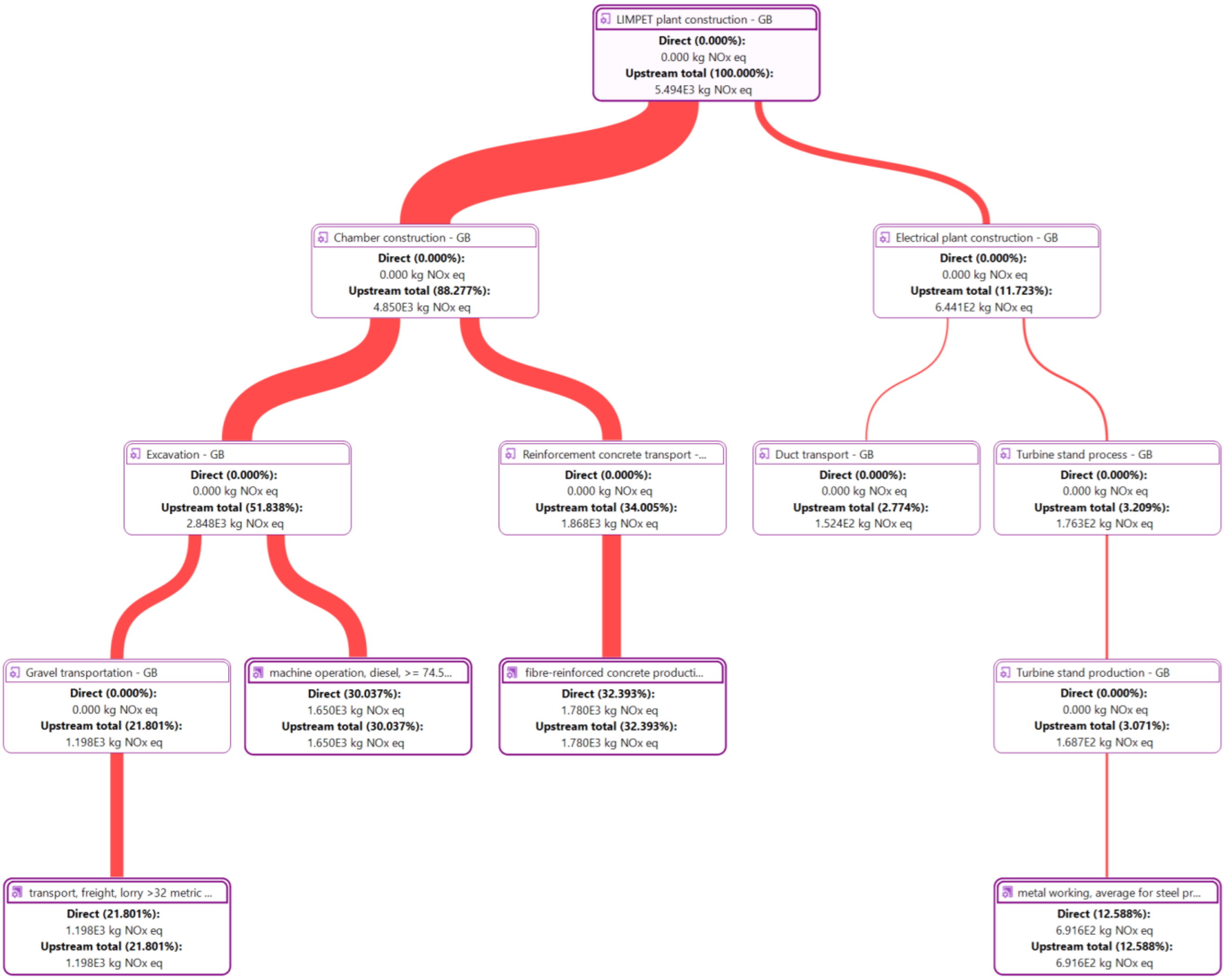
Human carcinogenic toxicity



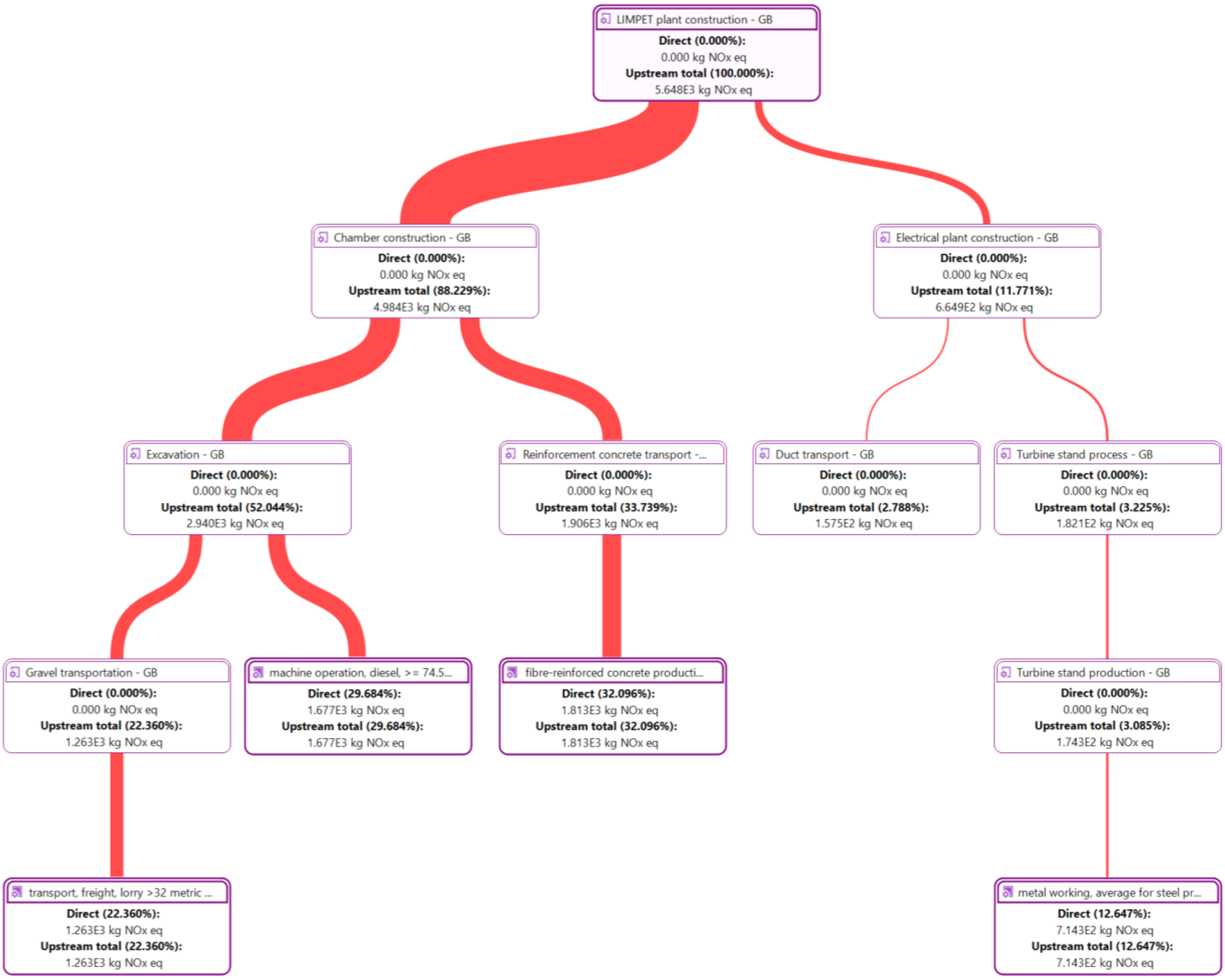
Human non-carcinogenic toxicity



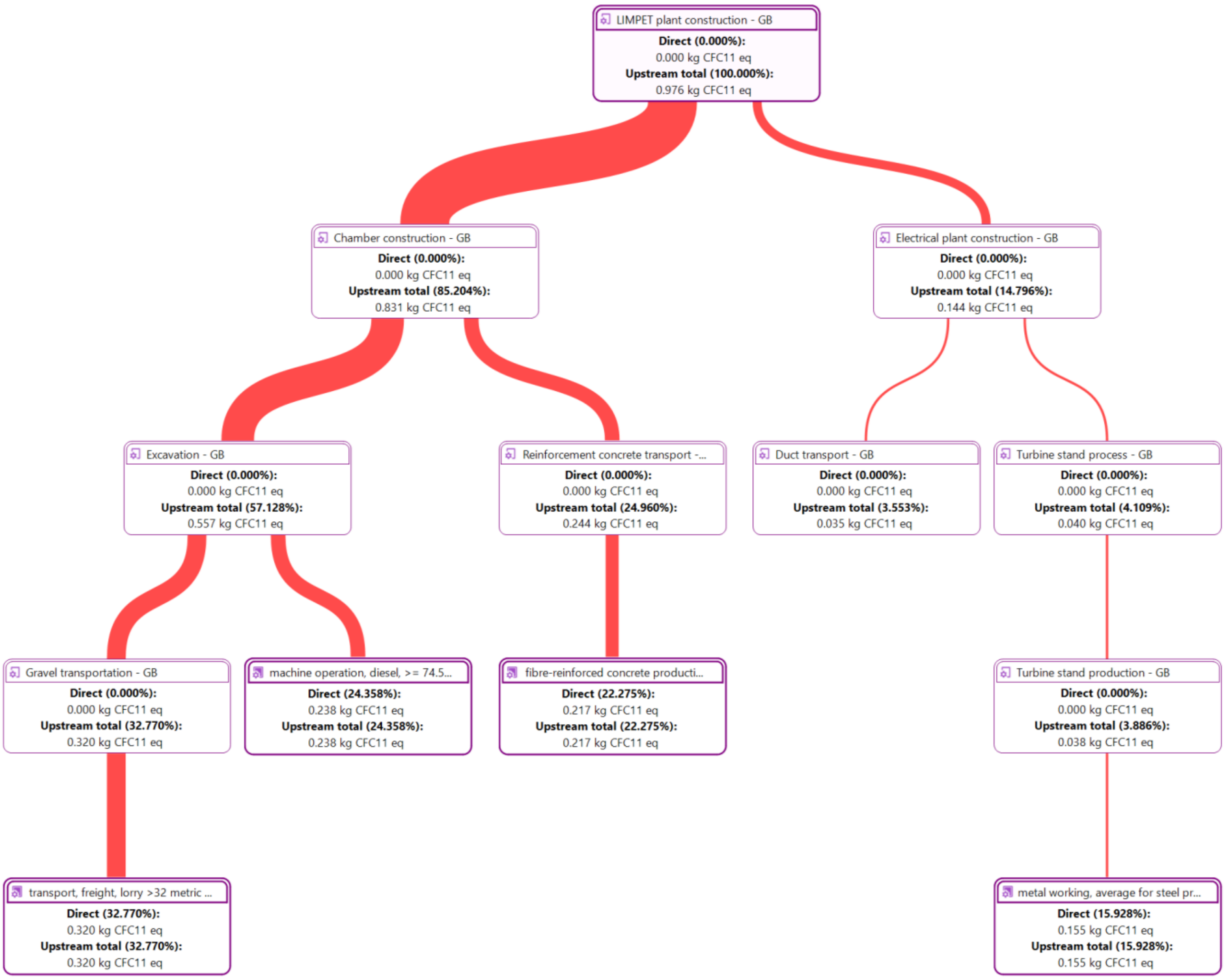
Ionizing radiation



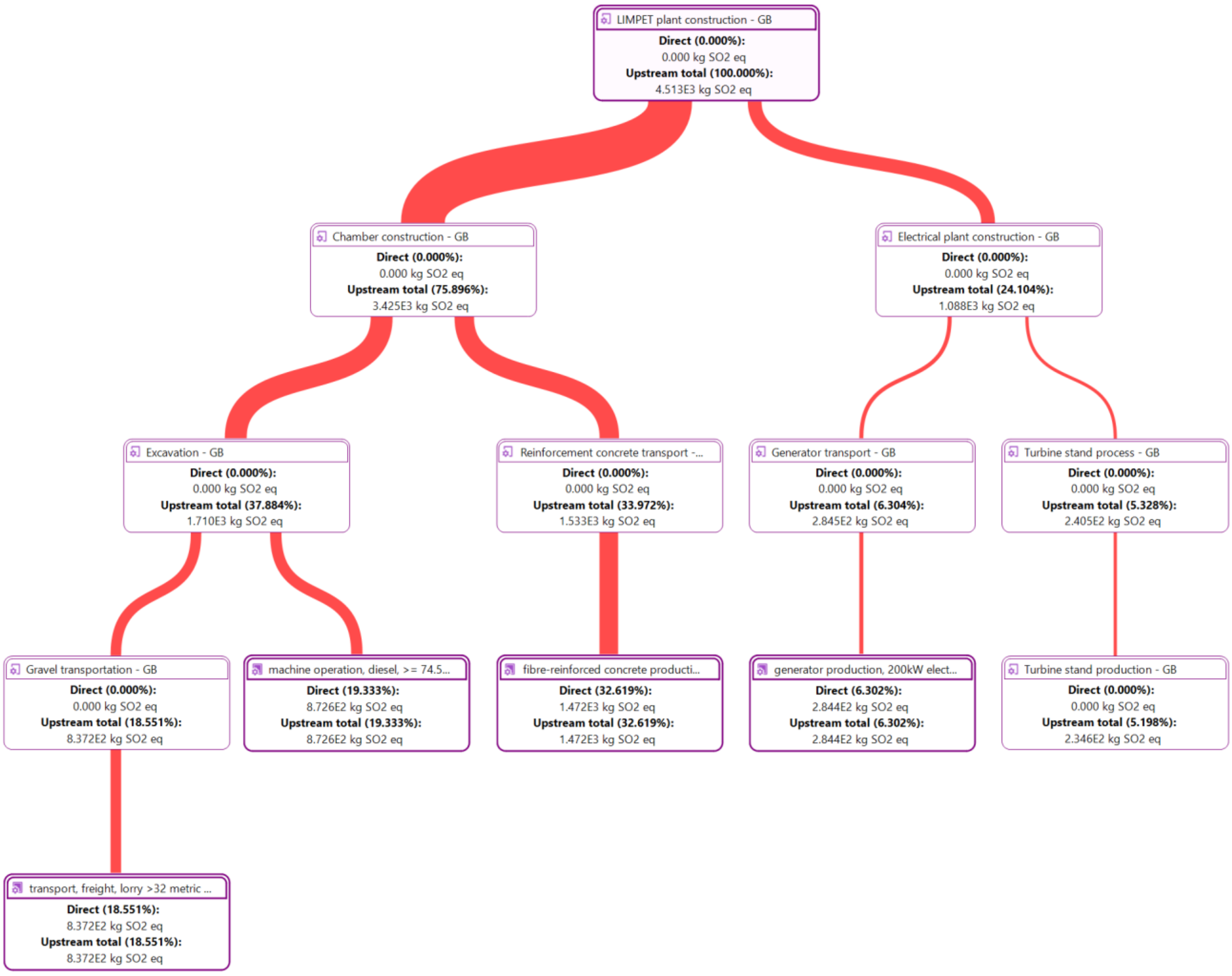
Ozone formation, Human health



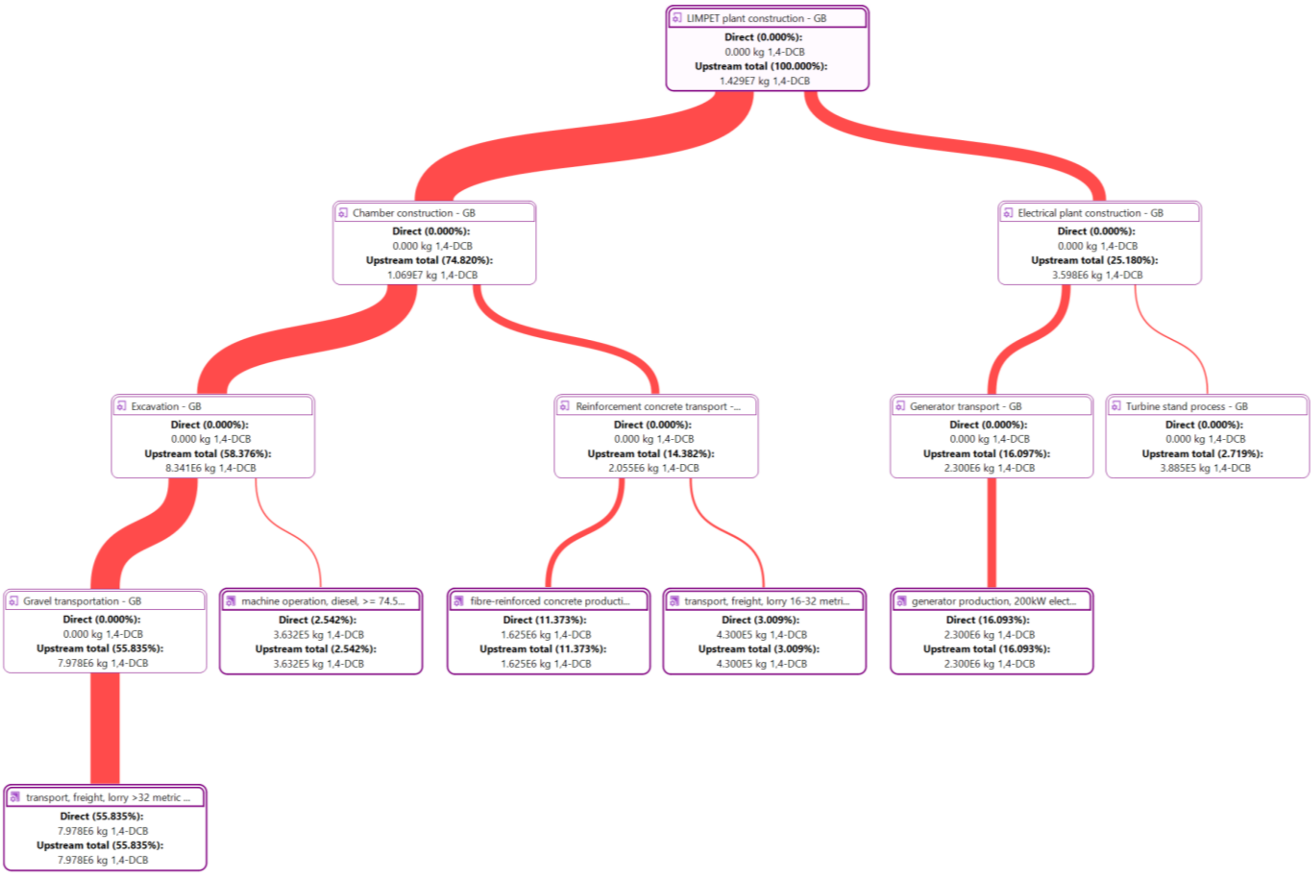
Ozone formation, Terrestrial ecosystems



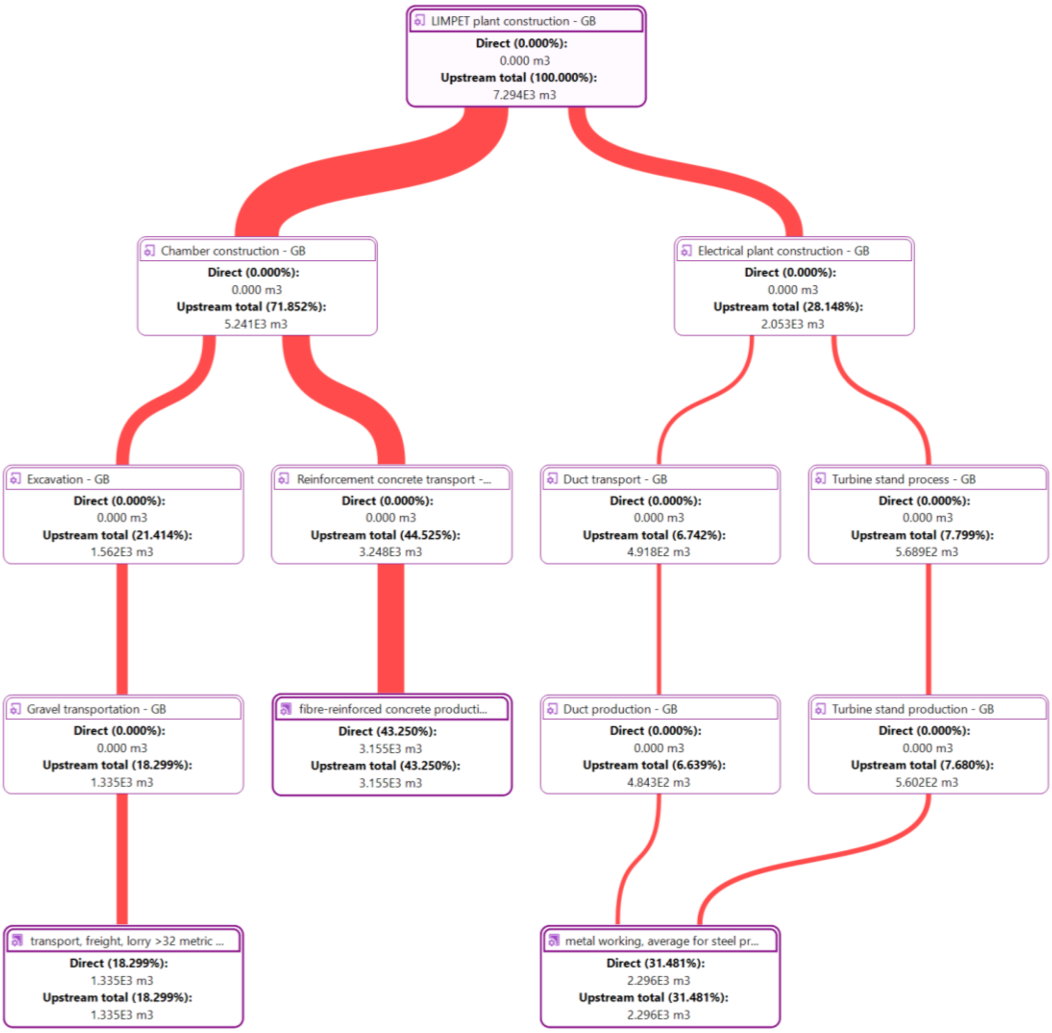
Stratospheric ozone depletion



Terrestrial acidification



Terrestrial ecotoxicity



Water consumption

Appendix B Master's research proposal

University of
South-Eastern Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

Master's Thesis

Title: Life cycle analysis of ocean wave energy convertor.

USN supervisors: Gamunu Samarakoon Arachchige, Marianne S. Eikeland

External partner: University of Sri Jayewardenepura, Sri Lanka (NORPART ReTech project)

Task background:
Ocean wave energy has a large global resource with immense potential for clean energy. To harness this energy, several types of ocean wave energy convertors (WEC) are designed, developed, and evaluated in the field for research purposes as well as commercial applications. Coastal blowhole as such has untapped potential as WEC, ye they have received limited attention from the research community.

However, these onshore and offshore renewable projects can have a high environmental impact during the construction of the plant, production, and distribution of the energy. As these technologies develop, Life Cycle Assessment (LCA) is effective tool for measuring and minimizing the environmental impact resulting from electricity generation project as such. This thesis aims to develop the knowledge on LCA of WEC and conduct a LCA of natural blowhole phenomenon-based wave energy convertor.

Task description:
The main goal of this project is to perform an LCA of an ocean WEC based on the natural blowhole phenomenon to identify its potential environmental impact. This involves several key tasks including conducting a comprehensive literature review of current ocean WECs (state-of-the-art) and related LCA studies and developing an LCA model for the entire process of the natural blowhole-based ocean WEC (i.e., cradle-to-gate assessment).

Student category: Reserved for an exchange student.

Is the task suitable for online students (not present at the campus)? ~~Yes~~/No

Practical arrangements:
OpenLCA software and the Ecoinvent database are the tools of choice for LCA.

Supervision:
As a general rule, the student is entitled to 15-20 hours of supervision. This includes the necessary time for the supervisor to prepare for supervision meetings (reading material to be discussed, etc.).

Signatures:

Supervisor (date and signature): Gamunu Samarakoon 21.02.2024

Student (write clearly in all capitalized letters):

HESHANKA SINGHAPURAGE

Student (date and signature):

23/02/2024